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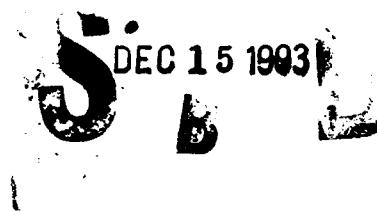
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*Repair, Evaluation, Maintenance, and Rehabilitation Research Program*

## **Redevelopment of Relief Wells, Upper Wood River Drainage and Levee District, Madison County, Illinois**

by *J. A. Kissane*  
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<u>Problem Area</u>		<u>Problem Area</u>	
CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

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# **Redevelopment of Relief Wells, Upper Wood River Drainage and Levee District, Madison County, Illinois**

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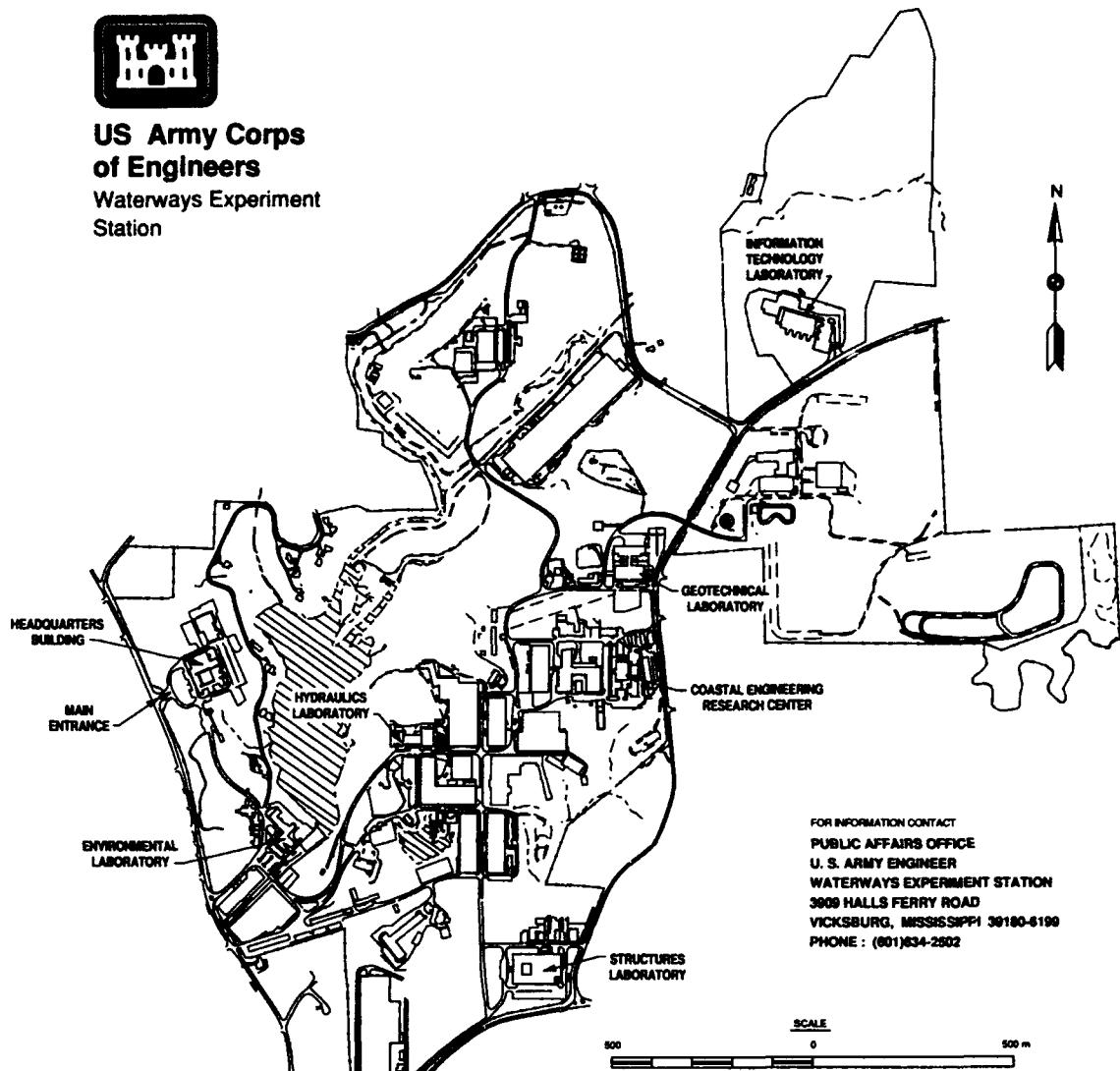
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# Preface

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The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of Geotechnical (Soils) Problem Area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under Work Unit 32643, "Alternative Treatments for Rehabilitation of Relief Wells and Drains," for which Mr. Roy E. Leach, U.S. Army Engineer Waterways Experiment Station (WES), was Principal Investigator. Mr. Joe A. Kissane was the assigned Principal Investigator for the U.S. Army Engineer District (USAED), St. Louis. Mr. Arthur Walz (CECW-EG) was the REMR Technical Monitor for this work.

Mr. William N. Rushing (CERD-C) was the REMR Coordinator at the Directorate of Research and Development, HQUSACE; Mr. James E. Crews (CECW-O) and Dr. Tony C. Liu (CECW-EG) served as the REMR Overview Committee; Mr. William F. McCleese, WES, was the REMR Program Manager. Mr. Gene P. Hale, Geotechnical Laboratory (GL), WES, was the Problem Area Leader.

The study was performed under the general supervision of Dr. Don Banks, Chief, Soils and Rock Mechanics Division, GL; Dr. Paul F. Hadala, Assistant Director, GL; and Dr. William F. Marcuson III, Director, GL. The work undertaken at Wood River was performed under the general supervision of Messrs. George J. Postol, Jimmy Bissell, and Michael J. Klosterman, USAED, St. Louis. Logistical assistance and coordination was provided by Messrs. Everett Pate and Larry Green, USAED, St. Louis.

During publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

# Conversion Factors, Non-SI to SI Units of Measurement

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Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
Fahrenheit degrees	5/9	Celsius degrees or kelvins <sup>1</sup>
feet	0.3048	metres
gallons (U.S. liquid)	3.785414	cubic decimetres
inches	25.4	millimetres
pounds (force) per inch	175.1268	newtons per metre
pounds (mass)	0.4535924	kilograms
square inches	6.4516	square centimetres

<sup>1</sup> To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula:  $C = (5/9)(F - 32)$ . To obtain Kelvin (K) readings, use:  $K = (5/9)(F - 32) + 273.15$ .

# 1 Introduction

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## General

By authority of the Flood Control Acts of 1936 and 1938, the U.S. Army Engineer District (USAED), St. Louis, undertook extensive measures to upgrade levees along the Mississippi River. The upgrading of the levees resulted in their ability to hold back higher river stages, which in turn resulted in increased underseepage. In the past, levee stability had been threatened by the formation of sand boils caused by uncontrolled underseepage. Underseepage controls installed along the levees included berms, relief wells, and pump stations. Most of the relief wells in the Mississippi River Levee Districts in the St. Louis District were installed in the early to mid-1950's.

## Objective

The construction of Melvin Price Locks and Dam (formerly Locks and Dam 26(R)) has resulted in increased river stages immediately above the dam, and a consequential increase in underseepage upstream of the new dam.

This report describes the efforts to rehabilitate existing relief wells as partial mitigation of increased underseepage and includes detailed descriptions of redevelopment procedures that may be useful on wells of this and similar designs. It is anticipated that the results of the testing and analysis of the data will be useful in assessing the needs for ongoing maintenance of relief well systems, in addition to providing documentation of the work performed at this site.

The redevelopment was performed in multiple phases. The first phase included treatment of a group of wells with a combination of trisodium phosphate (TSP) and sodium hypochlorite (HTH), and surging. This first phase work was performed from January through March 1987 by personnel of the St. Louis District. Two wells were cleaned by Alford Rogers Cullimore Concept (ARCC), Inc., as a demonstration project using a patented process called blended chemical heat treatment (BCHT) (Appendix A). The second phase was performed by ARCC, Inc., from January through March 1989 using the newly patented BCHT process on the wells treated in Phase 1. The third

phase consisted of the treatment of a set of 41 wells located downstream of those treated in Phases 1 and 2 using TSP, HTH, surging, and intermittent pumping. The Phase 3 work was performed from October through December 1989 as a portion of the Melvin Price Locks and Dam Third Stage Cofferdam construction contract by J. S. Alberici, primary contractor, and McClelland Engineering, subcontractor.

## Location and Project Description

The Upper Wood River Drainage and Levee District is located on the Illinois side of the Mississippi River bounded on the upstream end by the existing Lock and Dam 26 structure at Alton, IL, and on the downstream end by the mouth of the Wood River at the Mississippi River (Figures 1 and 2.) The relief wells included in this work are located along the landside toe of the upstream portion of the levee.

The relief wells of the Upper Wood River District consist of 8-in.<sup>1</sup>-inside diameter (ID) wood stave well screens, wood riser pipes, gravel filter, sand backfill, and concrete upper backfill. A schematic of the original well design is shown in Figure 3. The screens are perforated with 3/16-in. ( $\pm 1/32$ -in.) vertical slots, and the bottom of the screens are closed with wooden plugs (Figure 4). Tops of the relief wells are protected with corrugated metal guards and fitted with valves to prevent backflow of material into the wells. The levee embankment, drainage system, and well guards have recently been modified to accommodate anticipated underseepage requirements resulting from completion of the new lock and dam. Wells were designed with an average actual aquifer penetration of 60 percent to achieve equivalent aquifer penetration of 50 percent after well loss considerations. Well depths range from 58.8 to 78.83 ft (installation depths). Screen length varies from 19.4 to 54.8 ft.

## Geology and Aquifer Description

The foundation sediments of the Upper Wood River District consist of a sequence of floodplain deposits underlain by alluvial sands, glacial alluvium and outwash, and in some locations, glacial till overlying limestone or at some locations shale bedrock. These sediments are 60 to 110 ft thick, depending upon surface elevation. The major aquifer units are the Pleistocene Glasford and McHenry Formations. The overlying floodplain deposits consist of silty clays, clayey silts, and silty sands. The thickness, composition of, and aerial extent of the floodplain deposits determine whether the aquifer behaves as confined, semiconfined, or unconfined.

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<sup>1</sup> A table of factors for converting non-SI units of measurement to SI units is presented on page vii.

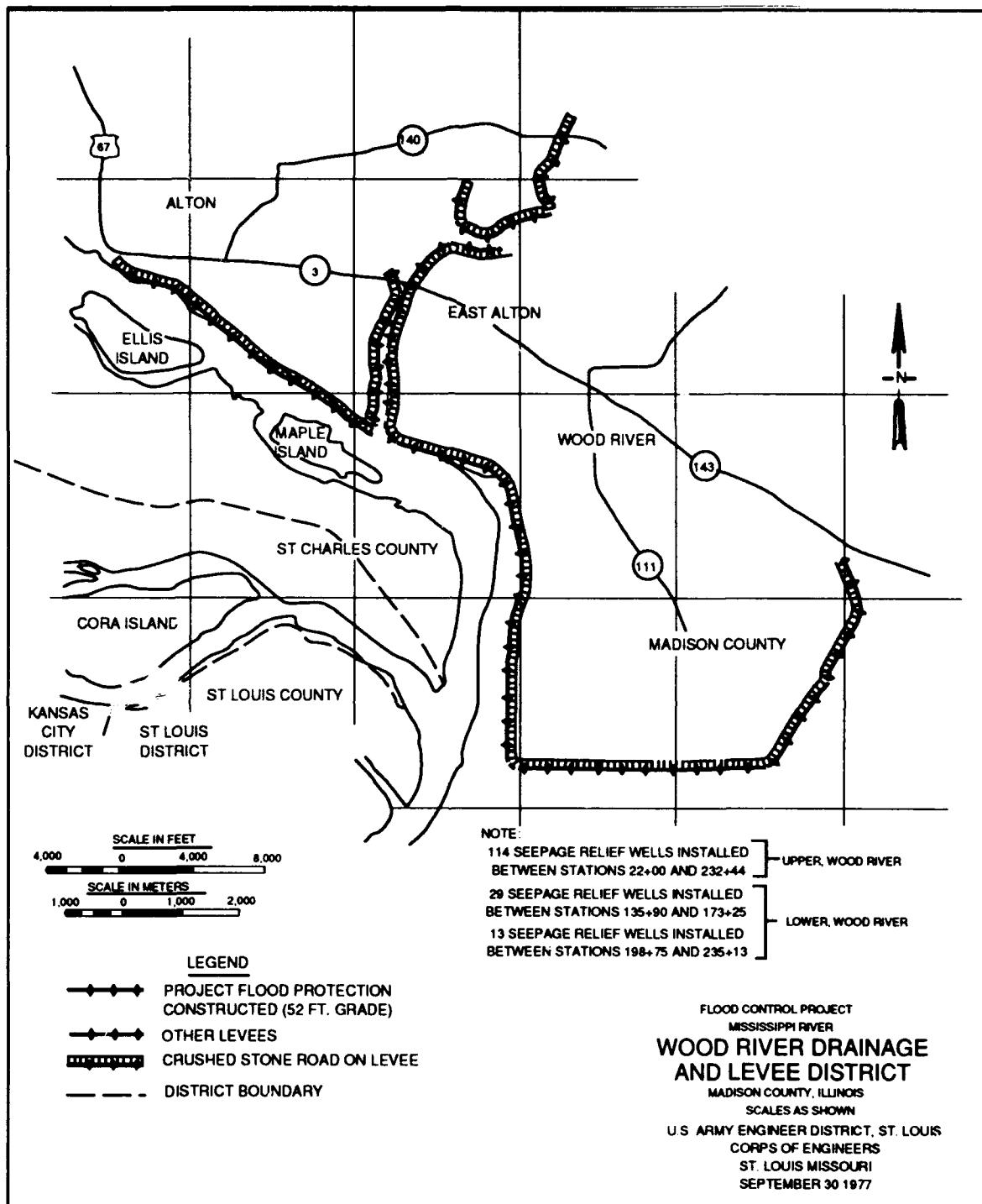


Figure 1. Map of study area

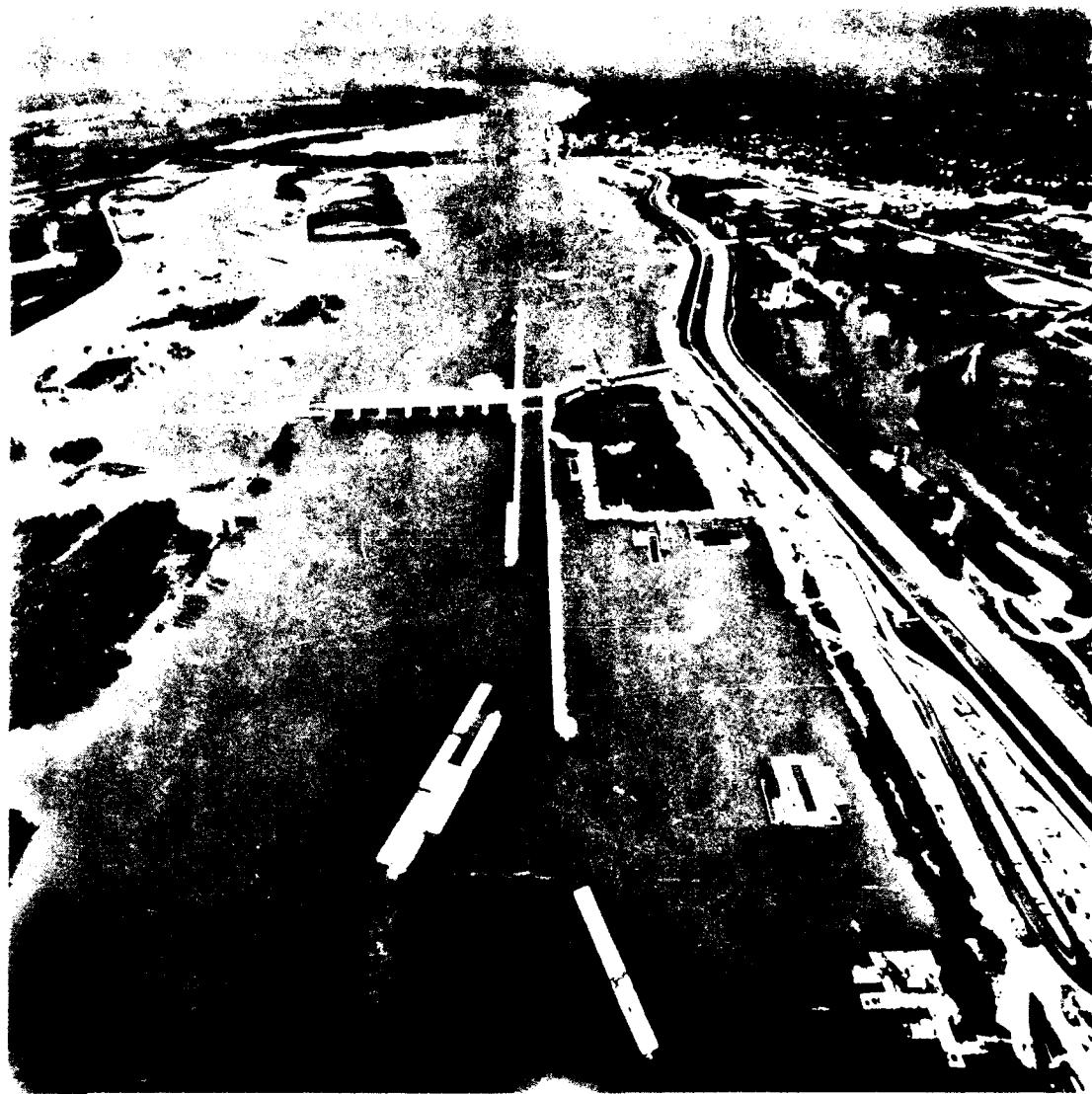


Figure 2. Work area

This depositional sequence results in a foundation that has generally coarser sediments at greater depths grading upward into finer sediments. The soil profiles from boring logs and well installation reports are contained in Figures 5 and 6. Permeabilities of the sands below the floodplain deposits range from  $800 \times 10^4$  to  $3,000 \times 10^4$  cm/sec, with an average of  $1,650 \times 10^4$  cm/sec (based upon tests of partially penetrating wells and grain-size analysis performed in 1956). The static groundwater elevation is largely dependent upon the river stage and the proximity to dewatering activity associated with the construction of Melvin Price Locks and Dam. The depth to groundwater

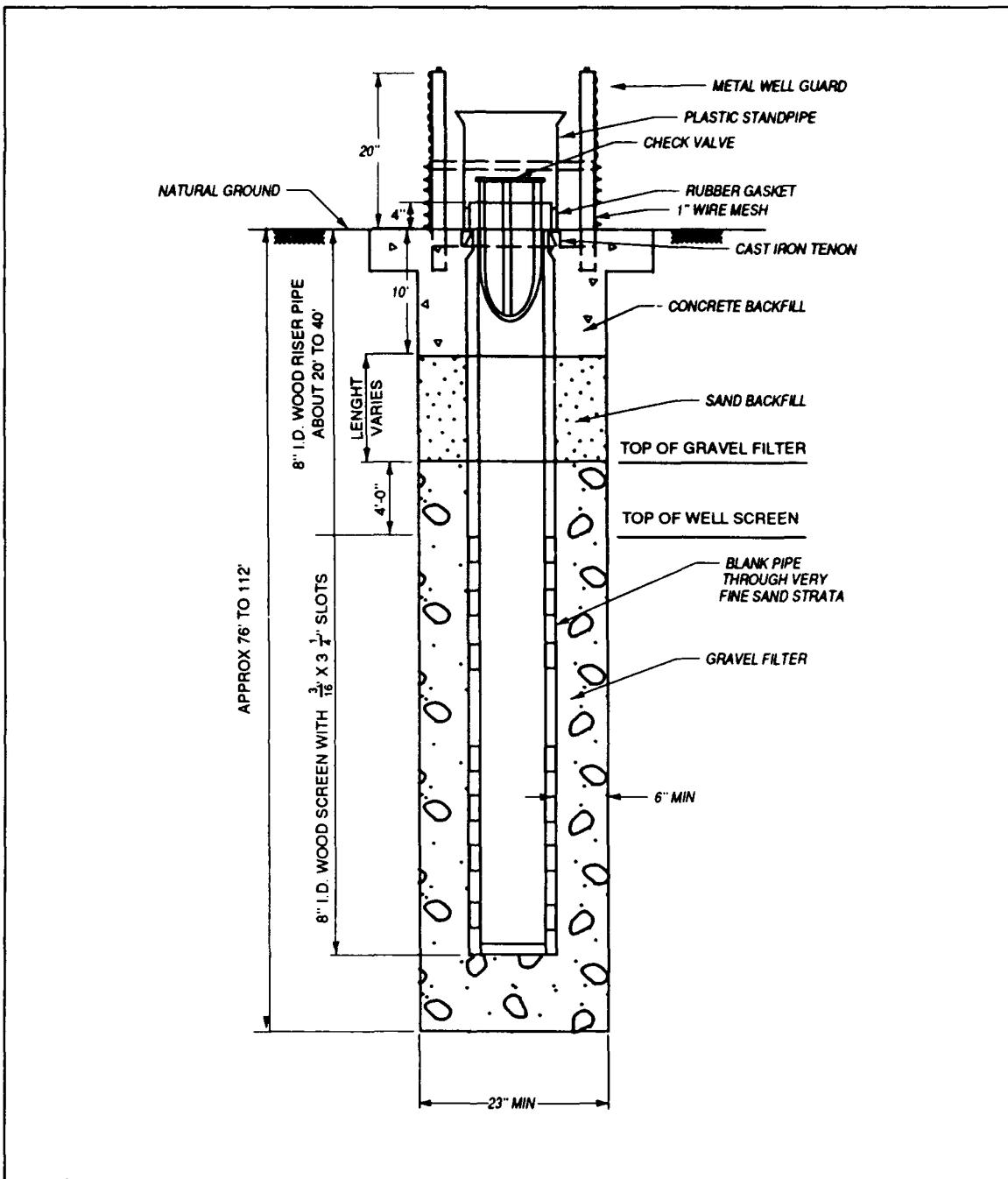


Figure 3. Schematic drawing of typical relief well



Figure 4. Wooden stave well screens prior to installation

groundwater in the relief wells ranged from 7 to 39 ft below the ground surface at the time this work was conducted, with the lower groundwater depths directly across the Mississippi River from the dewatered cofferdam and construction area.

The groundwater elevation in the wells during the first phase redevelopment work was found to be between 4 and 6 ft above the level recorded at the time the wells were installed. This difference has in some cases changed the aquifer from an unconfined to a confined or semiconfined state, because of the elevation of the boundary between the floodplain and alluvial deposits. This change in aquifer character was not universal throughout the study area because of the varying thickness and aerial discontinuity of the floodplain deposits.

One effect of this change in the groundwater environment is to lower the numerical value of the specific capacity in the cases where the aquifer has changed from unconfined to confined. The apparent decrease in specific capacity for aquifers having the physical parameters of these sediments (i.e. transmissivity in the range of 150,000 to 300,000 gal/day/ft, and the hydraulic conductivity ranges given above) ranges from 18 to 25 percent. This range is derived empirically, and the actual conversion is likely to be site specific. The conversion is further complicated by the possibility of the change in character from confined to semiconfined or leaky, during the course of work or even during a pump test. Test results were likely to be influenced by the closeness of the groundwater level to the aquifer-aquitard contact and the proximity of a major recharge source (the Mississippi River).

Accurate logs of the stratigraphic contacts within each well were not available prior to the redevelopment program, and natural gamma logs of some of the wells have been made to further define the subsurface conditions that may have impact upon data analysis. These logs are included in this report as Appendix B.

## Previous Studies

A program of testing to evaluate the ongoing performance of underseepage controls was undertaken following the installation of relief wells in the drainage and levee districts within the St. Louis District along the Mississippi River from Alton to Gale, IL. Each relief well was tested for specific capacity at the time of installation, and wells within each district were designated as test wells for future study. Designated wells were periodically tested and the results compared with the initial test data. Testing of the designated wells was conducted in 1957, 1960, 1969, 1973, and 1976. Data from test wells in the Upper Wood River District are limited to Wells 36 and 92X. The results of the prior tests are contained in Montgomery (1972) and USAED, St. Louis (1976a and 1976b).

The general conclusions of the earlier works are that the wells declined in effectiveness after installation, but the rate of decline decreased with time. In addition to this observation, the studies of the wells and their response to the Flood of 1973 indicate that the wells improved to nearly their original effectiveness as a result of the prolonged period of flow during the flood. Evaluation of flow data from the Flood of 1973 indicated restored yields in some of the test wells of slightly higher than 100 percent of the original values. Tests in 1976 indicated an overall average of 78 percent of original specific capacity. Examination of the test wells following the flood indicated a substantial reduction in iron bacteria, iron, and magnesium in the well water and a decrease in pH. It is presumed that a certain amount of mechanical redevelopment and flushing of bacterial residue occurred as a result of the high flows. The same studies indicated that the test wells of the Upper Wood River District showed the least improvement of those in any District following the flood. The significance of this observation is not certain as only two wells from the Upper Wood River District were included in the comparisons.

The consideration of whether the aquifer was in a confined, unconfined, or semiconfined state during the previous studies was not made. This consideration may significantly alter validity of conclusions based upon the test data, if the data were interpreted as though conditions were constant. The manner in which the change from the confined to unconfined condition or vice-versa affects pump test results will be described in the discussions of test results in Chapter 5 of this report.

Additional information is given in Applin and Zhao (1989); Hadj-Hamou, Travassoli, and Sherman (1988); Mansuy (1988); and U.S. Army Engineer Waterways Experiment Station (WES) (1956 and 1989).

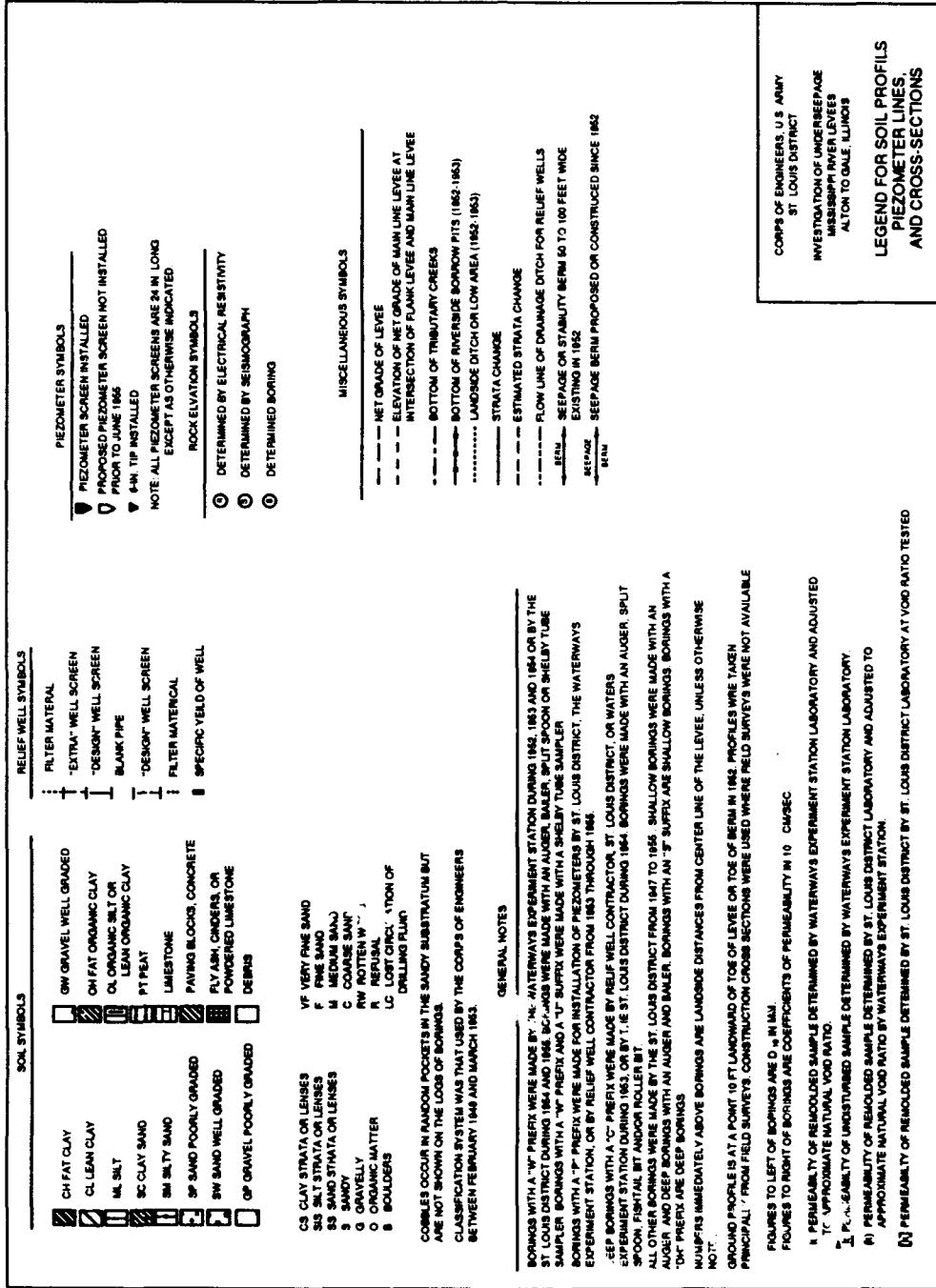


Figure 5. Explanation of soil profiles

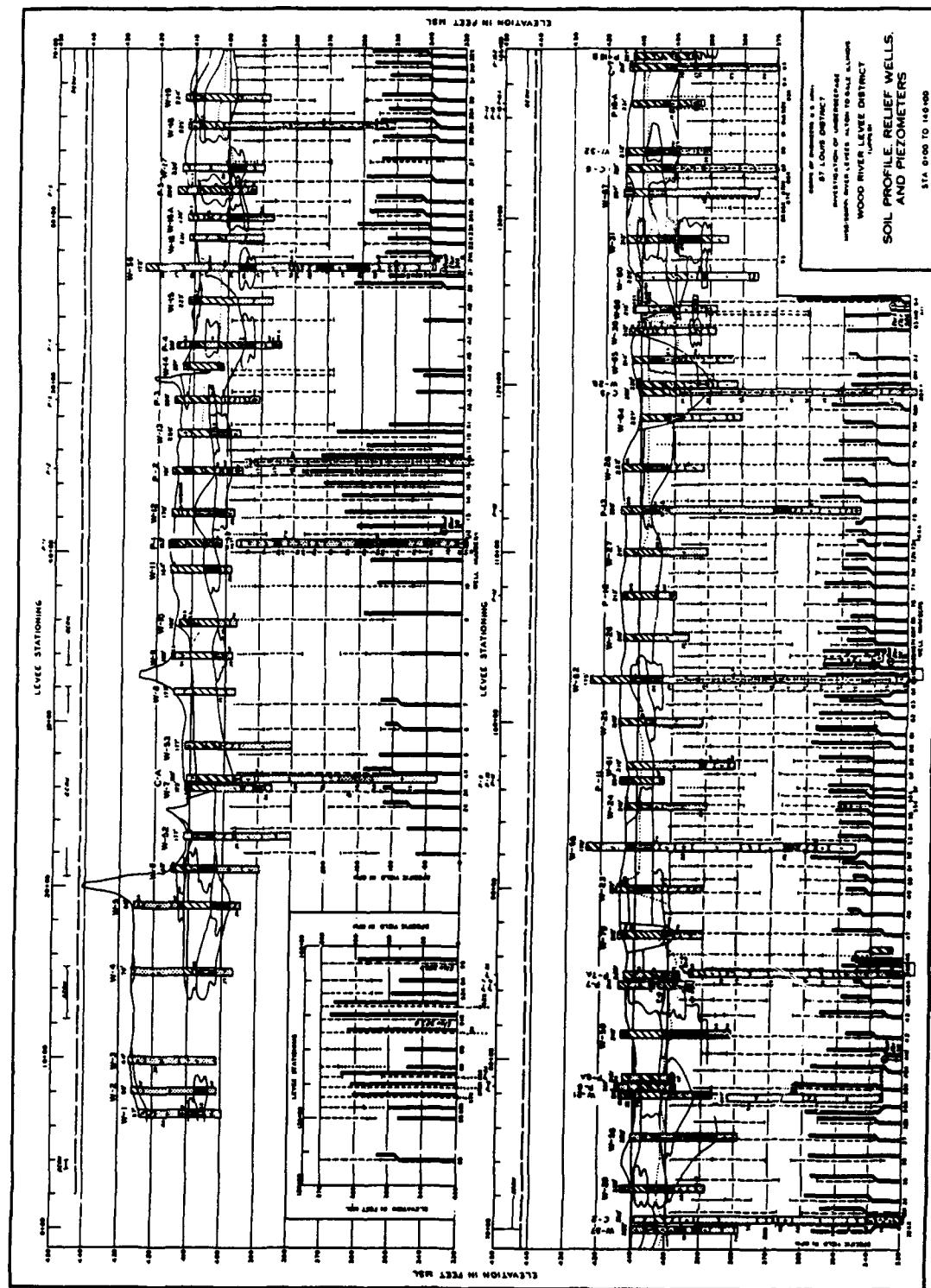


Figure 6. Soil profiles of study area

## 2 Description of Problem

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### Purpose

The primary purpose of this redevelopment program was to maximize the efficiency of existing underseepage controls, specifically the relief wells, thereby minimizing the need for additional wells. It was determined by evaluating design criteria for the levee and well system that wells not reaching 80 percent of their installation specific capacity should be considered for replacement. The cost of nearly \$25,000/well for recently installed wells in the District provided a substantial incentive to find an efficient and less costly alternative to replacement.

The construction of Melvin Price Locks and Dam and the subsequent raising of the river stage adjacent to the Upper Wood River District has had a marked impact on the local groundwater conditions. The local groundwater levels will be consistently higher upstream of the dam than they had been in the past, and the differential head across the levee has been increased. If these changes in groundwater conditions are not adequately mitigated by underseepage controls, there may be negative impact on existing nearby property and structures (i.e. flooding of basements, low areas, etc., or formation of sand boils during floods).

It is anticipated that some if not all of the relief wells in the District upstream of the new dam will experience nearly constant flow as a result of the raising of river stage. The design of these wells was based upon seasonal or high-water flow, and the full effects of continuous flow are not yet known. This program of testing and redevelopment of the existing relief wells was undertaken to optimize the efficiency of existing measures, evaluate the effectiveness of redevelopment techniques, and assist in assessing the number and location of additional wells needed. The results of these tests are also part of the ongoing periodic evaluation of underseepage control measures in the St. Louis District.

## Bacterial Action on Wells

It has long been believed that a primary cause of well decline or loss of efficiency is the growth and accumulation of organisms collectively referred to as "iron-related bacteria" (IRB) and "sulfate-reducing bacteria" (SRB). These organisms are present in some concentrations in nearly all shallow-depth freshwater wells in North America. The specific genera and the concentrations present are functions of environmental conditions including Eh, pH, temperature, and dissolved concentrations of iron and other substances.

Bacteria cause decline of well efficiency by obstructing the open volume of the well screen, filter, and surrounding aquifer. The obstruction is the result of the accumulation of the bacteria themselves, precipitated ferric hydroxide around the cells, and the metabolic production by some organisms of extracellular excretions which serve as additional sites of ferric hydroxide precipitation.

## Common Diagnostic Types of Bacteria in Groundwater

The presence of certain bacteria in groundwater and wells may indicate environmental conditions that are related to well performance. The various types of bacteria described below are not exclusive taxonomic groups; i.e., a particular genus of bacteria may occur in a wide enough range of conditions that it may belong to more than simply one group.

The term "iron-related bacteria" or "IRB" has been historically used to describe any bacteria that precipitate, reduce, or oxidize iron in some form. The description implies nothing else about the environment or characteristics of the bacteria.

Sulfate-reducing bacteria (SRB) generally proliferate in an environment rich in organic material (nutrient rich) with sufficient sulfate ion concentration and a deficiency of oxygen (anaerobic conditions). These bacteria tend to precipitate ferrous sulfide as a metabolic by-product.

Heterotrophic bacteria require organic carbon and are therefore an indicator of its presence. Oligotrophic bacteria are heterotrophic and also tend to occur where there is an abundance of oxygen (aerobic conditions) and where groundwater may otherwise be nutrient poor. This group does not tend to be a major factor in well decline.

Facultative and fermentive bacteria are considered eutrophic, or indicative of an abundance of nutrient material. Facultative bacteria, although not major contributors to well decline, indicate that significant nutrient material is present and may occur in either aerobic or anaerobic conditions. Fermentive bacteria

contribute to well decline by generating acidic by-products from the metabolism of sugars. The acidic by-products may corrode metallic well screens.

Testing conducted during the initial redevelopment efforts indicated that substantial populations of bacteria of the *Gallionella* and *Pseudomonas* genera are among the varieties of IRB present. The *Gallionella* genus is a very common variety and has been found to be responsible for biofouling in wells worldwide. It is a bacteria which uses iron in the reduced state as an energy source during oxidation. *Gallionella* bacteria are typically bean-shaped cells that produce a very easily distinguished stalked extracellular structure. The *Pseudomonas* genus includes bacteria with a variety of environmental habits, generally heterotrophic, that adsorb colloidal iron into their cell walls and collect iron in extracellular extensions.

Visual evidence of IRB infestation is present at the surface adjacent to many of the wells in the form of reddish iron oxide staining of the concrete pad from well discharge. Downhole videocamera inspection of the wells during the initial redevelopment efforts indicated concentrations of suspended filamentous material (assumed to be largely a result of bacterial infestation) in the well water in concentrations that made visibility nil prior to pumping the wells. Following pumping (to clear the water), downhole videocamera inspection indicated that well water and screens contained highly visible concentrations of filamentous material and residue.

## Other Possible Causes of Well Decline

Other contributing factors in the decline of well efficiency are certainly possible. Downhole videocamera inspection indicated some areas of possible mineral accumulation (most likely calcium carbonate or iron and/or magnesium carbonate) in some screens. These occurrences were not extensive and were not regarded as very significant in the overall reduction of well efficiency. The process of "silting in" results when very fine material migrates into the filter material, clogging it or reducing its conductivity. This can be caused by improper or incomplete well development, bridging of filter material during installation and subsequent separation, extreme overpumping, or incorrect filter design. Records of surging and bailing performed at installation indicate that the filter material was properly designed and that the wells were properly developed. The prolonged period of flow during the Flood of 1973 apparently did not cause any detectable damage to the wells (as might be expected had the filter material been improperly designed or installed) and, in fact, is believed to have improved their efficiency in some cases. Surging operations performed during the initial redevelopment work did not produce the large amounts of fine-grained material that would be expected if the filter material had become silted in.

Backflow into the wells and consequent contamination, or the possibility of contamination by material falling into the wells, is not believed to be a

significant contributor to well decline. The design of the protective structures (see Figure 3) are such that only minimal backflow is possible. The accidental entry of foreign material into the wells is possible (as indicated by remnants of small animals pumped out of one well) but is not likely on a large scale.

Vandalism is a possible source of well decline, but it is not likely that such a large group of wells would be vandalized in its entirety. There is no evidence that vandalism on such a scale has been committed, and all well guards were found to be secured at the start of this work. Individual wells (specifically Nos. 37, 37X, and 42) were found to have been vandalized or damaged (without record) to the extent that redevelopment was not possible.

## Limitations of Wooden Screen

The use of wooden stave screens was justified at the time of installation based upon considerations of cost and corrosion resistance. Downhole video-camera inspection verified the condition of the well screens to be good, particularly considering their age. The use of these screens has had an impact on the methods and procedures which may be used to rehabilitate them.

The screens as constructed have an open area of 30 sq in./linear foot of slotted section, which is equivalent to 10-percent open area. Approximately 1 ft of each section of screen is not slotted, to allow for coupling. The open area, then, is slightly less than 10 percent. This is low, compared with commonly used wire-wrap screens, which typically have 30-percent open area, or newer slotted screens having open areas approaching 20 percent. As a result of this, there is less area for flow into the wells, and clogging of the slots, therefore, has a greater impact on efficiency. The ability of any redevelopment efforts to treat the filter and adjacent aquifer is limited by the low open area of these screens.

The slot size (3/16-in.) limited the design of the filter material and the tolerance of the filter to vigorous surging. Surging at higher travel speeds was found to pull even coarse-grained material through the screen and damage the filter. This limited the surging rates that could be used in redeveloping the wells.

The wood used in the well screens and risers is creosote-treated fir and is fairly soft. Any efforts to mechanically redevelop these wells had to consider the risk of damaging the wells by vigorously surging or pressurizing the wells. The wooden plugs used at the bottoms of the wells are also fragile, and care was required to avoid damaging them during redevelopment.

For all of these reasons, surging of these wells was a more labor-intensive and time-consuming task than would be the case with wire-wrap screened wells.

## Groundwater Environmental Factors

The groundwater level in the project area is a function of recent rainfall and the stage of the Mississippi River. Changes in the river stage adjacent to the area are reflected almost immediately in the water levels in the wells. A recent drought and the impact of dewatering activities at Melvin Price Locks and Dam had lowered water levels in the wells, particularly those closest to the construction site. The methods used to pump and redevelop the wells had to be compatible with the water levels in the wells. The dewatering activity had lowered the water level in some wells to the extent that the uppermost portions of well screens were exposed to air or would be exposed in the course of pumping and redevelopment. Work on these wells had been scheduled for a period of time when no dewatering was in progress because the mechanical action of the water during surging and pumping is an integral part of the redevelopment process. The water level in some wells was lower than the lifting capability of centrifugal pumps. The equipment used in this program included centrifugal pumps and high output 6-in.-diam submersible turbine pumps.

The total impact of the changes in the groundwater environment as a result of increased river stage upstream of the new dam on the relief wells is not known. It is assumed that many of the wells upstream of the new dam will flow continuously. The Flood of 1973 produced a period of flow of nearly 3 months from some wells along the Mississippi River. The studies of the impact of that flooding on relief wells indicated that the well effluent water took on chemical characteristics closer to that of the river water than typical well water tests in the past. This included a lowering in pH from an average of 7.34 in 1969 to 6.81 in 1976 in wells tested. Substantial drops in concentration of iron and IRB were also noted in the wells tested in 1969 and 1976.

The area adjacent to the project may have undergone other changes that have had an effect upon the groundwater environment as well. The area had previously been one of industrial activity, with operational factories of Owens-Illinois and Olin Metalworks located immediately adjacent to the site. These facilities ceased operation in the early 1980s. The city landfill of Alton, IL, is also located adjacent to the upstream edge of the site, and its influence on the biochemical character of the local groundwater is undetermined. No effort is made here to determine the impact of these factors upon the relief wells.

## 3 Redevelopment Procedures

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### Development Chronology

Redevelopment of the wells near the Wood River pumping plant occurred during three nonconsecutive periods of time between January 1987 through December 1989. Phase 1 followed a typical set of well rehabilitation specifications varying certain mechanical and chemical aspects in an attempt to produce an optimum set of specifications. During Phase 1, a demonstration of the new BCHT procedure was conducted on two wells. Phase 2 was conducted using only the BCHT process. Phase 3 was another attempt to use standard procedures of treatment using TSP and HTH. These phases of development are shown on Table 1.

### First Phase Redevelopment

An initial effort was made by the St. Louis District to redevelop a group of the relief wells to the desired 80-percent performance level, using a set of procedures specified in the contract for the new Alton Pump Station as a guideline. The redevelopment of these wells was deleted from the contract to allow the District to evaluate the procedures without the constraints of other contractual schedules and restrictions. The procedures were based upon mechanical surging combined with chemical treatment and pumping. The wells were treated with TSP, a wetting agent to assist in separation of fine-grained material and bacterial debris from the filter material and adjacent aquifer, and HTH, a disinfectant to reduce the bacterial impact on the wells.

Prior to the initial redevelopment work, the wells were pump tested and found to have declined to an average of approximately 60 percent of their installed specific capacities. The actual numerical values for installation specific capacities ranged from 123 to 324 gal/min/ft, and because of this wide range of values, test results expressed as percentages of installation values for each well are used to evaluate the results of the program.

**Table 1**  
**Phases of Redevelopment**

Phase 1: Thirty-two wells were tested and a program of redevelopment proceeded using TSP, HTH, and surging. Amounts of chemicals added and amount of surging was varied throughout the course of work to evaluate effectiveness. Phase 1 also included a pilot test of BCHT techniques. Mean improvement of 21 gal/day/ft in specific capacity resulted overall in Phase 1.

Phase 2: Twenty-eight wells previously treated in Phase 1 were treated using BCHT techniques. Wells were initially pump tested and their bacterial and chemical characteristics checked with field testing kits. Wells were then treated with gaseous chlorine, sulfamic acid, proprietary surfactants and steam, with waiting intervals in between. Mean improvement of 14 gal/day/ft resulted overall in Phase 2. This is in addition to Phase 1 improvement in these wells.

Phase 3: Fifty-nine wells not included in Phases 1 and 2 were pump tested and forty-one were prioritized for redevelopment. Redevelopment consisted of treatment with TSP and HTH and intermittent pumping. This work was performed as part of a larger construction contract with firmly defined procedures as to amount of surging, pumping, and quantities of chemicals added to wells. Mean improvement of only 2 gal/day/ft overall resulted. These wells included those most severely impacted by the dewatering activities at Melvin Price Locks and Dam, and the marginal results may reflect that fact.

Included in the contract specifications were the design of the surge block, the rate of travel of the surge block, and details of a required chemical treatment. Redevelopment procedures were to include an initial pump test, treatment with a glassy polyphosphate and HTH, a waiting period of 24 to 36 hr, a period of surging followed by removal of infiltrate, and another series of chemical treatment, waiting, and surging. A final pump test was specified to evaluate well efficiency following redevelopment. Phase 1 redevelopment is summarized in Table 2.

Each well was initially pump tested to determine the specific capacity before treatment. Figure 7 shows the pump and equipment setup during a typical pump test. Testing was done with a 6-in. trailer-mounted centrifugal pump, an in-line dial flowmeter, and an electric water level indicator. Water level readings were taken at frequent time intervals during the first several minutes of the test and less frequently as the test progressed (times varied, but in general the readings were taken every minute for the first 5 or 10 min and every 5 min for the next 15 or 20 min and every 15 to 30 min for the remainder of the test). Discharge was measured by monitoring the flowmeter with a stopwatch and recording the flow rate at the time of each drawdown reading. Drawdown data were recorded to the nearest one-hundredth of a foot. Tests were usually conducted for a minimum of 90 min and were not considered complete until two consecutive drawdown readings showed no change. A field calculation of specific capacity was made by dividing discharge by final drawdown (without correction for well loss or other factors). If the field value of the specific capacity was at least 80 percent of the installation value, no further action was taken to redevelop the well.

**Table 2**  
**Phase 1 Redevelopment**

Dates: January through April, 1987

Number of Wells: 32

Well Numbers: 14, 15, 16, 17, 18, 19, 20, 21, 21X, 22XX, 23X, 24X, 25, 26, 27, 28, 28X, 29X, 30, 31, 31X, 32X, 32XX, 33X, 34, 35, 36, 43, 43X, 44X, 45X, 46

Type of Wells: 8 in-ID creosote-impregnated wooden casing and screen. Vertical saw-cut type screen sections, length of screen and depth of wells varied.

TREATMENT: \*\*\* Initial pump test

\*\*\* Compared with installation pump test

\*\*\* TSP and HTH added  
(concentrations varied)

\*\*\* Well surged in "cycles" of 15 passes  
(number of cycles varied)

\*\*\* Intermediate pump test

\*\*\* Additional chemicals and surging  
(varied)

\*\*\* Final pump test

2 wells used in pilot test of BCHT

MEAN INSTALLATION SPECIFIC CAPACITY: 139 gal/min/ft

MEAN SPECIFIC CAPACITY PRIOR TO TREATMENT: 84 gal/min/ft

MEAN SPECIFIC CAPACITY FOLLOWING TREATMENT: 105 gal/min/ft

\*\*\* Dewatering at Melvin Price Locks and Dam ongoing throughout Phase 1. Resulting cone of depression increased in depth toward higher numbered wells, but groundwater levels were generally 4 to 6 ft above level at time of well installation.

Visual examination of the material brought out of the wells during the pump tests were made to assist in evaluating the pretreatment condition of the wells.

Following the initial pump test, each well (except those above the 80-percent criterion) was treated with a mixture of TSP and HTH. The chemicals were added to water and mixed in a barrel before being added to the well water. In general the volume of water in the well was roughly calculated, and 5 to 10 lb of TSP and 2 to 3 lb of HTH per 100 gal of well water were added.

The mixture of chemicals and water was pumped into the well from the barrel and mixed by agitating with the surge block. One well (No. 19) was surged without chemicals for simple comparison.



Figure 7. Centrifugal pump and lines used in Phases 1 and 2

A waiting period followed the addition of chemicals to the wells. This waiting period was designed to allow the TSP to act as a dispersing agent and assist in separating clay particles and other materials from the sand in the filter. The ideal waiting period described in the specifications was between 24 and 36 hr. Actual waiting periods during the program ranged from 2 to 36 hr. By varying the waiting period and observing the results of subsequent tests, it was believed that some relationship between waiting period and the effectiveness of chemical treatment could be determined. The 2-hr waiting period was considered inadequate after reviewing test results and recommendations from the WES. The 36-hr limit is important as that is the maximum time that the sodium hypochlorite is effective in acting against bacterial growth that may be stimulated by the TSP.

Surging was performed using a surge block consisting of a central steel 3-in. pipe with an arrangement of wooden and rubber washer-like rings at each end (Figure 8). The rubber rings were designed to be slightly smaller in diameter (7-in.) than the inside of the wells (8-in.). A fine-wire chimney brush was added to the configuration to assist in removal of bacterial slime and scale. The surge block was connected to the winch cable of a drill rig usually parked at the shoulder of the highway adjacent to the wells (Figure 9). Pulleys were located at the drill rig and the top of the well to facilitate the procedure.



Figure 8. Surge block used in Phases 1 and 2



Figure 9. Surging of wells using drill rig

The amount of surging and the rate of travel of the surge block were varied as work progressed and as different operators were used. The Alton Pump Station contract specifications required a rate of travel of 1.5 to 2.0 ft/sec, and this rate was followed for some of the work. Surging rates were increased to 2.5 ft/sec for most of the wells. Well 35 was surged at a rate closer to 5 ft/sec, and a small amount of coarser material was brought into the well as a result. Surging operations as described in the specifications were to be done in "cycles," which were defined as 15 passages of the surge block up and down the entire length of the well screen. The total number of cycles used ranged from 3 to 50 cycles.

Two wells (29 and 22X) were treated with a commercially marketed sulfamic acid product designed to assist in well restoration. Well 29 was treated by adding the prescribed amount of acid to the well water and mixing it with two cycles of surging. After a waiting period of 18 hr, the well was surged an additional two cycles and pump tested and only minor improvement (4 percent) was noted. Well 22X was treated by adding the acid to the well water and mixing with two cycles of surging. After a waiting period of 18 hr, the well was surged for an additional 10 cycles and pump tested. Well 22X showed only slightly more gain than Well 29 (6 percent).

A measurement of infiltrate was made following each surging operation. A determination was then made as to whether or not cleanout was necessary. Cleanout during the initial phase of redevelopment was accomplished using a plastic pipe connected to the intake of a 2-in. centrifugal pump. Visual observations of the amount and general appearance (content, grain size, amount of organic residue, etc.) of infiltrate were used as qualitative means of evaluating the condition of each well.

Most of the wells were given one or more intermediate pump tests to evaluate the effectiveness of the first series of surging and chemical treatment. Redevelopment efforts indicated that it was unlikely that the wells would reach the desired 80-percent criterion after the first series of surging, and to save time and effort, the intermediate tests were eliminated from the procedures late in the program. For the wells treated later in the program, a second round of chemical treatment, waiting, surging, and cleanout immediately followed the first series of surging and cleanout.

A final pump test was performed on each well to determine the amount of improvement over the initial test results and to evaluate the performance of the wells relative to installation data.

The results of the first phase of redevelopment indicated that a point of diminishing return of improvement per amount of effort was reached beyond which redevelopment efforts (specifically surging) were only marginally effective. This relationship is demonstrated by the plot in Figure 10.

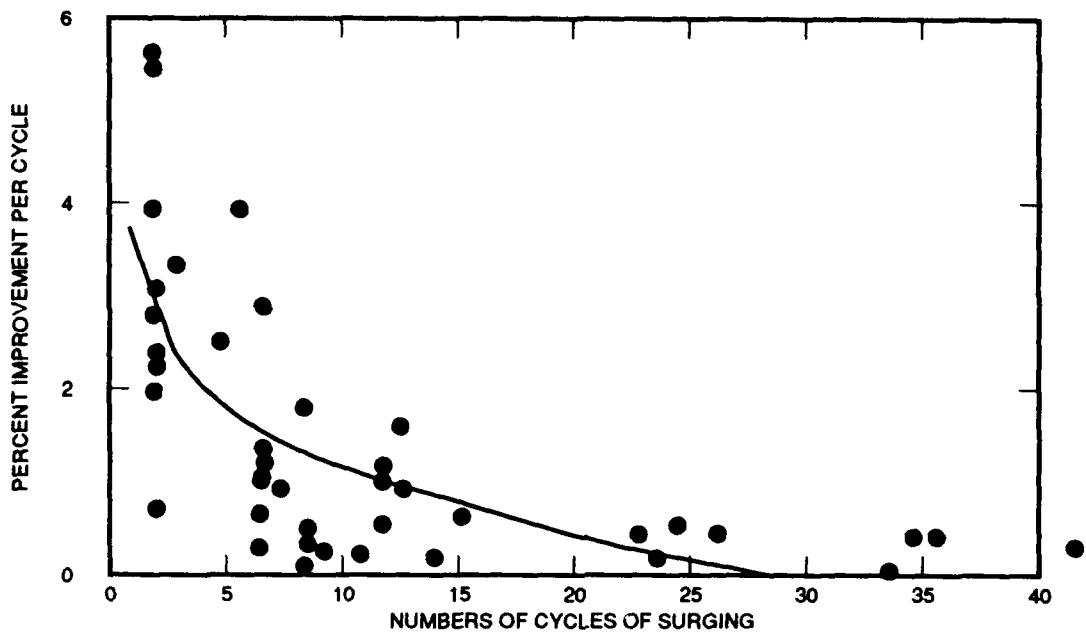


Figure 10. Plot showing decrease in effectiveness of surging with increase in amount of surging

Wells 37, 37X, 41X, and 42 were found to be obstructed and not accessible to surging. The obstructions in Wells 37 and 37X were such that initial pump tests were not possible. Pump tests were performed on the other two obstructed wells, and all four were scheduled for downhole videocamera inspection to evaluate the nature of the obstructions.

Because of disappointing results using the standard procedure that combined TSP and HTH, a demonstration of the BCHT process was performed by ARCC, Inc. This newly patented redevelopment technology (discussed in Appendix A and in Phase 2 redevelopment) was demonstrated during Phase 1 on two wells already treated by the St. Louis District to the assumed point of diminishing return (Wells 44X and 46). The results of the demonstration indicated that the BCHT method had the potential of achieving 12- to 14-percent improvement in wells that had already been treated to the assumed limit of effectiveness by the earlier methods.

## Second Phase Redevelopment BCHT

The review of the results of the initial phase of redevelopment indicated that present procedures would not bring the wells up to design specifications.

It was decided that ongoing research at WES (Appendix C) seemed to indicate a bacterial encrustation problem and that a steam and chemical cleaning procedure, BCHT, being evaluated (demonstrated in Phase 1) should be implemented to increase the well-specific capacities. The demonstration of the newly patented BCHT process was performed by ARCC, Inc., on two wells already treated by the St. Louis District to the assumed point of diminishing return (Wells 44X and 46). The results of the demonstration indicated that the BCHT method had the potential of achieving 12- to 14-percent improvement in wells that had already been treated to the assumed limit of effectiveness by the earlier methods.

In principle, the BCHT method relies upon a three-stage concept of treatment. The first is the "Shock" stage, designed to shock and disrupt infesting bacterial populations. The second stage, the "Disrupt" stage, involves the use of heated dispersing/wetting agents and steam in combination with surging to separate the bacterial residue from the filter and aquifer. The third stage, the "Disperse" stage, involves the removal of the bacterial residue and whatever fine-grained material is brought into the well by the processes.

The potential to achieve desired 80-percent performance combined with the complication and expense of replacing existing relief wells were factors in the decision to use BCHT methods on wells not at the 80-percent level of performance following the first phase treatment. Wells within a given reach that were not at 80 percent of their installed specific capacity would have to be replaced on a nearly one-for-one basis because of the high permeability of the aquifer and low radius of influence of each well. As demonstrated, the BCHT method could be applied at a cost of approximately \$4,000/well, including the cost of surging and pump tests performed by St. Louis District personnel.

This project also presented a good opportunity to demonstrate the BCHT methods on a fairly large number of similar wells for which detailed background and historical data were available.

This new redevelopment method is under patent by the ARCC, Inc., as documented in Appendix C. The procedures in general include an initial well diagnosis performed with a prepackaged field microbiological test kit, which is designed to give a qualitative indication of the types of bacterial and chemical agents at work in the wells, and a very general indication of the concentrations. Tests performed during this project included the tests for IRB, SRB, slime-forming bacteria, and a general bacterial count test (referred to in the Contractor's records as "Dip-n-Count"). The initial pH and temperature of the water were also measured prior to treatment. Treatment was then designed with the information from the tests in mind, targeting the problematic agents with an appropriate set of chemicals. As described above, redevelopment of the wells using the BCHT methods is based upon three principal elements of treatment:

- a. *Shock.* This phase is achieved by adding chlorine to the well and surrounding aquifer to "shock" kill or reduce the impact of deleterious bacteria. Exact chemical use may be regulated by State or Federal agencies.
- b. *Disrupt.* This phase is achieved by the addition of chemical agents and steam to the well and surrounding aquifer and surging to break up organic and mineral clogging in the system. Surfactants are used to hold the particles in suspension until the disperse phase.
- c. *Disperse.* This phase of treatment consists of removal (by whatever means is most applicable) of the material that is clogging the well and aquifer.

Initial water samples were taken from the wells before the start of the BCHT redevelopment activities. The test results from the field test kit were not available immediately (the usual time delay is about 3 days from when the samples are taken). Previous biochemical data from other wells in the District were available from earlier work, and a treatment was designed based upon the assumption that the available data would agree with the field test kit results. Phase 2 redevelopment is summarized in Table 3.

Treatment began with an initial injection of highly chlorinated water into the well. Gaseous chlorine was batched with water to a concentration exceeding 800 ppm, as measured by a field test kit shown in Figure 11. The volume of each well was calculated and the chlorine solution injected in a volume three times that of the wells. This chlorine "shock" was then allowed to act on the well for a minimum of 24 hr. The choice of gaseous chlorine over powdered or granular chlorine products is based upon the belief that gaseous chlorine mixed into a solution has no components that might settle out of the mixture, and any other components of the dry chlorine compounds (such as calcium) are eliminated.

The next stage of treatment involved the injection of heated solutions into the well and surrounding aquifer. A portable steam generator was used to heat a chemical mixture which was then injected into the well through a specially designed mixing tube (Figure 12). The goal of this operation was to raise the temperature of the well water to a temperature of 120 deg F by internally circulating the well water and mixing it with the heated mixture. This temperature has been shown to kill nearly all bacteria in the well and surrounding filter. Each well was sealed, and a heated mixture of chlorine, sulfamic acid, and one of a group of patented polymers was injected into the well. The choice of polymer and the concentrations used were determined by ARCC, Inc., from the results of the tests performed at the start of the process, as it became available, or other previously available data.

The polymer/acid/chlorine mixture injected at this site had a pH between 1 and 2 and was pumped in at a temperature of approximately 200 deg F.

**Table 3**  
**Phase 2 Redevelopment**

Dates: January through February 1989

Number of Wells: 28

Well Numbers: 18, 19, 20, 21, 21X, 22X, 23X, 24X, 25, 26, 27, 28, 28X, 29X, 30, 31, 31X, 32X, 32XX, 33X, 34, 35, 36, 43, 43X, 44X, 45X, 46

Type of Wells: 8-in.-ID creosote-impregnated wooden casing and screen. Vertical saw-cut type screen sections, length of screen and depth of wells varied.

TREATMENT: \*\*\* Initial pump test

\*\*\* Compared with final Phase 1 pump test

\*\*\* Bacterial and chemical tests to determine extent of "biofouling"

\*\*\* BCHT. Acid surfactant and steam injected into wells (concentrations varied based on tests)

\*\*\* Well surged in "cycles" of 15 passes (number of cycles varied)

\*\*\* Intermediate pump test

\*\*\* Additional chemicals and surging (varied)

\*\*\* Final pump test

\*\*\* These wells were previously treated by Phase 1 methods.

MEAN INSTALLATION SPECIFIC CAPACITY: 137 gal/min/ft

MEAN SPECIFIC CAPACITY PRIOR TO TREATMENT: 133 gal/min/ft

MEAN SPECIFIC CAPACITY FOLLOWING TREATMENT: 147 gal/min/ft

\*\*\* Dewatering at Melvin Price Locks and Dam ongoing throughout Phase 2. Resulting cone of depression increased in depth toward higher numbered wells, but groundwater levels were similar to those at time of well installation.

Approximately 1.5 well volumes of the heated mixture were injected in each well. Injection pressure depended upon the "tightness" of the well, i.e. a less permeable situation would build higher pressures. Nozzle pressures were approximately 500 psi; however, this pressure dissipated within the well resulting in a lower overall pressure. The equipment in use at the site did not include the capability to measure well pressure, but that capability is planned for future projects by ARCC, Inc. Injection of the heated fluids is followed by a waiting period of approximately 48 hr. After the 48-hr wait, another batch

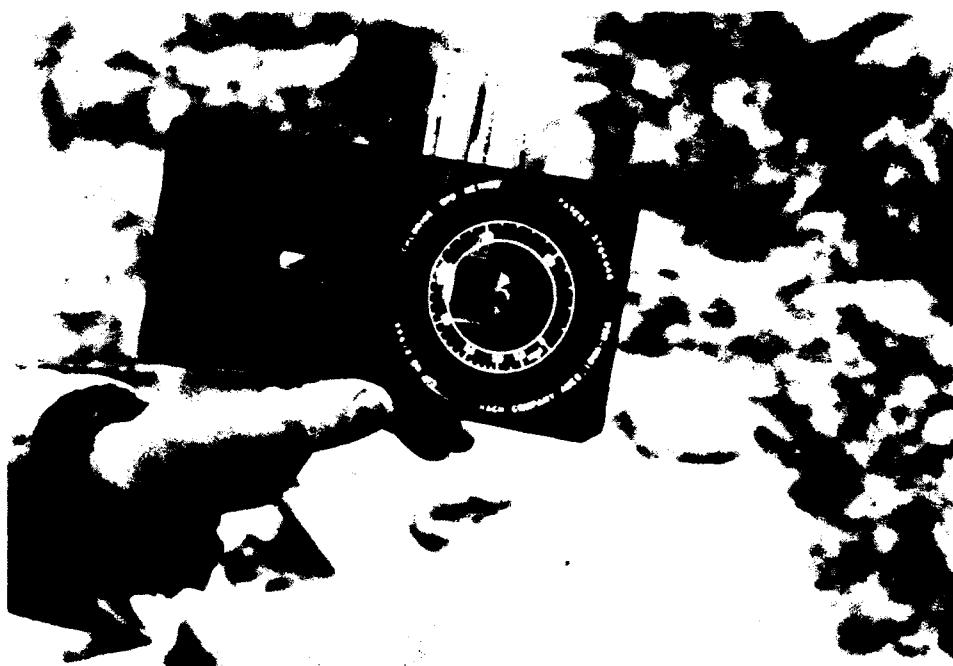


Figure 11. Colorometric test for chlorine concentration

of heated chlorine, acid, and polymer was injected into the well, in the same manner as the first batch, and the wells were left for another period of approximately 24 hr.

Following the 24-hr waiting period, the wells were surged with the same surge block configuration used in the first phase work. Surging consisted of approximately nine cycles (135 passes) of surging the length of the well screen at a rate of 2.5 ft/sec. Surging produced from 0.2 ft to slightly more than 1 ft of infiltrate in the wells. The wells were pumped with the centrifugal pump used in pump testing to remove the material brought in during surging. This pumping lasted 30 to 40 min. The drawdown information from this pumping was treated as an abbreviated pump test to provide a general idea as to the effectiveness of redevelopment. Another nine cycles of surging, followed by another short pumping period, and a final nine cycles of surging were performed, as additional efforts to improve the wells. The results of these "pump tests" are not exactly comparable with the final pump tests because they were not run to static drawdown.

The final stage of the treatment involved the "air lift" removal of infiltrate from the wells by pumping compressed air into the bottom of the well, and a final pump test to determine the total amount of improvement.

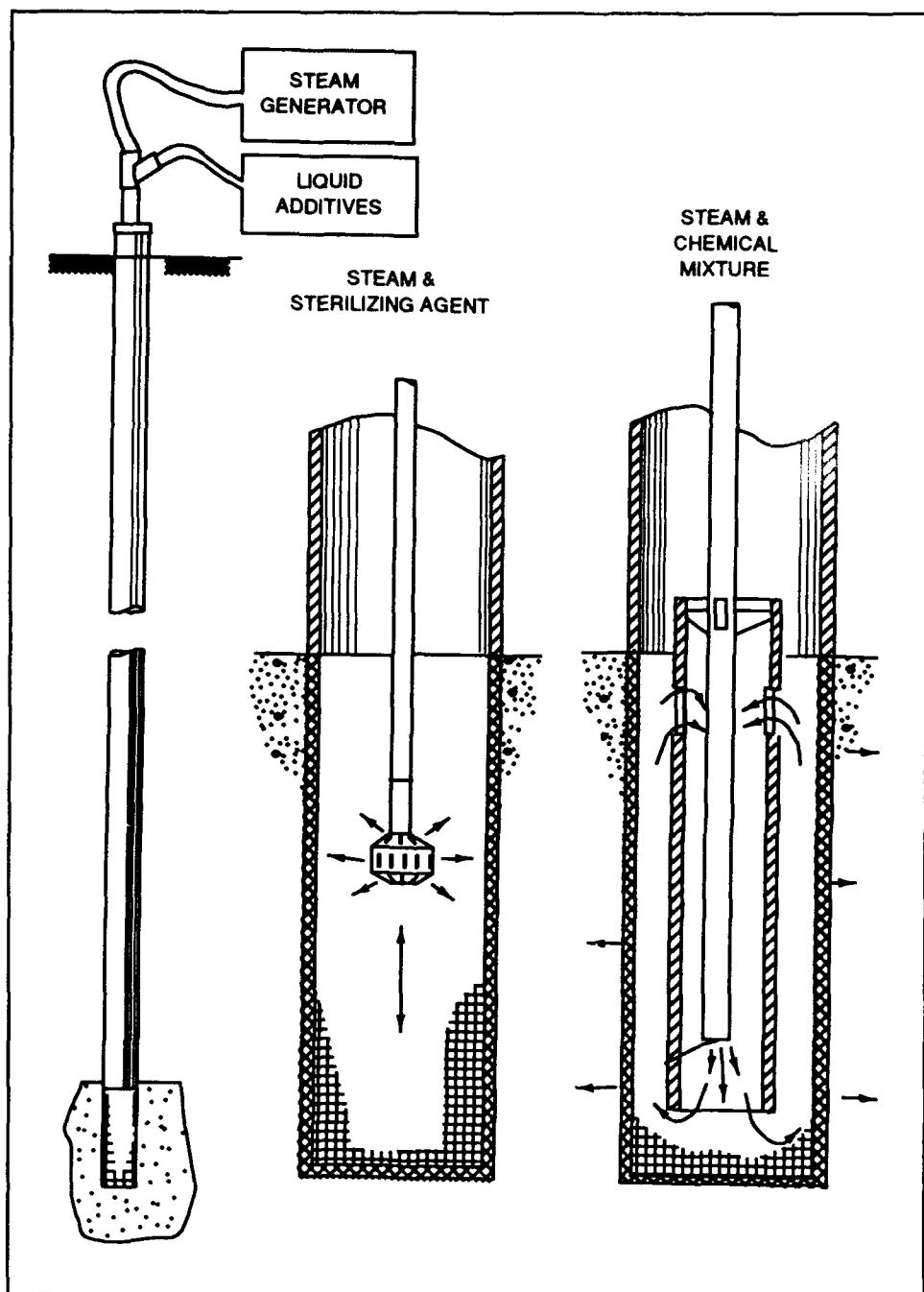


Figure 12. Schematic of BCHT mixing tubes (drawing courtesy of ARCC, Inc.)

## Third Phase Well Redevelopment

The time between the rewatering of the Phase 2 and dewatering of the Phase 3 cofferdams of Melvin Price Locks and Dam construction provided a time window during which the remaining relief wells adjacent to the project could be tested and redeveloped without the impact of dewatering. This work was performed as part of the Phase 3 cofferdam construction contract. The procedures were similar to the first phase redevelopment work. The contractor used high production 6-in.-diam submersible pumps and small cranes rather than the trailer-mounted centrifugal pump and drill rig arrangement. Phase 3 redevelopment is summarized in Table 4.

**Table 4**  
**Phase 3 Redevelopment**

Dates: October through December 1989

Number of Wells Initially Tested: 59

Number of Wells Treated: 41

Type of Wells: 8-in.-ID creosote-impregnated wooden casing and screen. Vertical saw-cut type screen sections, length of screen and depth of wells varied.

TREATMENT: \*\*\* Initial pump test

\*\*\* Wells prioritized based on results

\*\*\* TSP and HTH added  
(similar to Phase 1)

\*\*\* Well surged 3 "cycles" of 15 passes  
(similar to Phase 1)

\*\*\* Intermittent pumping for 1 hr

\*\*\* Final pump test

These wells were not previously treated in Phase 1 or Phase 2

MEAN INSTALLATION SPECIFIC CAPACITY: 139 gal/min/ft

MEAN SPECIFIC CAPACITY PRIOR TO TREATMENT: 76 gal/min/ft

MEAN SPECIFIC CAPACITY FOLLOWING TREATMENT: 78 gal/min/ft

\*\*\* Phase 3 performed during following rewatering at Melvin Price Locks and Dam between Stage 2 and 3 construction, so that no cone of depression affected water levels.

\*\*\* Groundwater levels in these wells were depressed below the tops of well screens prior to, but not during Phase 3 as a result of dewatering for construction.

The contract required the contractor to pump test each well for a minimum of 2 hr (similar to first and second phase work), at which time wells were prioritized as to which would be redeveloped first. This was necessary because the possibility that weather and the rising of the pool elevation upstream of the new dam could have delayed the redevelopment program, and consequently delayed progress of other aspects of the construction.

Redevelopment consisted of treatment with a mixture of TSP and HTH followed by surging and cleanout, intermittent pumping, and a final pump test. The chemical mixture consisted of 5 lb of TSP and 1 lb of HTH per 100 gal of water in the well and surrounding filter. This mixture was dissolved in water, pumped into each well, mixed using the surge block, and allowed to "work" for a waiting period of 24 to 36 hr. Surging was performed using small rubber-tired cranes at a rate between 1-1/2- and 3-ft/sec. Three periods of surging were performed, each consisting of 45 passages up and down the length of the well screen. A measurement of infiltrate was made after each period of surging and material removed if deemed necessary before proceeding. Following the last period of surging, the wells were intermittently pumped for 1 hr. This consisted of alternately pumping and not pumping at approximately 400 gal/min in 15- to 30-sec cycles. The intermittent pumping was intended to hydraulically surge the wells. Following the intermittent pumping, those wells requiring cleanout were bailed to remove infiltrate. Each of the wells was then pump tested a final time to evaluate their performance.

## Phase 1, 2, and 3 Well Water Sampling and Analysis

During the first phase redevelopment, samples of well water were taken by Dr. Al Mikell (research investigator for WES) from three wells within the District (Nos. 18, 37, and 97) and tested in the laboratory for bacterial content as well as iron content. Testing conducted during the initial redevelopment efforts indicated that substantial populations of bacteria of the *Gallionella* and *Pseudomonas* genera were among the varieties of IRB present. Results of analysis of these samples were used to verify the assumed presence of potentially deleterious bacteria populations in all the wells. The sampling was done with a peristaltic pump after pumping 20 L of water from each well.

Initial water samples were taken by ARCC, Inc., from Wells 44X and 46 before the start of the BCHT redevelopment process demonstration in Phase 1 and in each of the 28 wells treated by BCHT in Phase 2. These water samples were field-tested for specific types of bacteria using a Bacterial Activity and Reaction Test (BART) kit as part of the BCHT procedures. The BART kit results give the type of bacteria and a relative quantity present. These tests in general confirmed laboratory results for bacterial types.

A total of 11 wells were sampled by Dr. Mikell in January 1989 prior to the second phase BCHT redevelopment. A more detailed analysis of these

samples was performed to determine bacterial groups present. Wells were selected for this sampling based upon their varied response to the first phase redevelopment. The report of the findings of Dr. Mikell is included in this report as Appendix D.

## 4 Downhole Videocamera Inspection

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### General

Downhole videocamera inspection was performed using equipment specially designed for use in boreholes and wells. The camera is small enough to be used in holes of 3-in.-diam or greater. The unit obtained from the Corps of Engineers Southwest Division Laboratory is capable of recording black and white videotape footage in either of two modes: a side view mode, which records a view on either side of the camera as it travels in the hole (Figure 13), or a downhole mode, which records a view from the bottom of the camera as it travels in the hole (Figure 14). The downhole-viewing mode was not available during the initial phase of the program. An in-line counter is used to record the footage traveled by the camera. A small monitor is built into the recording unit. A larger auxiliary monitor may also be used to make viewing easier during the recording. Figure 15 shows the monitor and setup as used at the site.

Photographic reproduction from videotape footage does not produce high-resolution images, and those photographs included in this report are presented to illustrate specific features. The complete videotapes and log reports of this operation are on file at the St. Louis District.

### Downhole Videocamera Inspection Phase 1 Redevelopment

Downhole videocamera inspection was done on 11 wells within the District during the first phase of redevelopment to evaluate the physical conditions of the wells. This included two wells in which the water level was below the top of the screen (Nos. 83 and 86) and another well that is not otherwise included in this work (No. 5-A). Inspection was performed on wells at various stages of reconditioning and on the wells that were treated with the sulfamic acid to determine if any visual signs of improvement or damage could be observed.

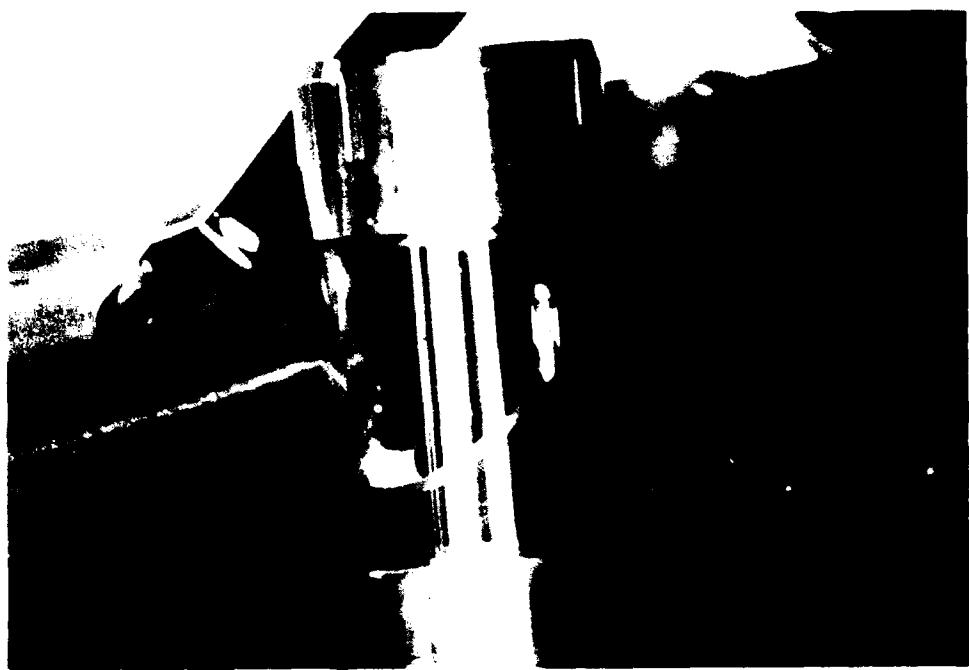


Figure 13. Side view looking head for downhole videocamera

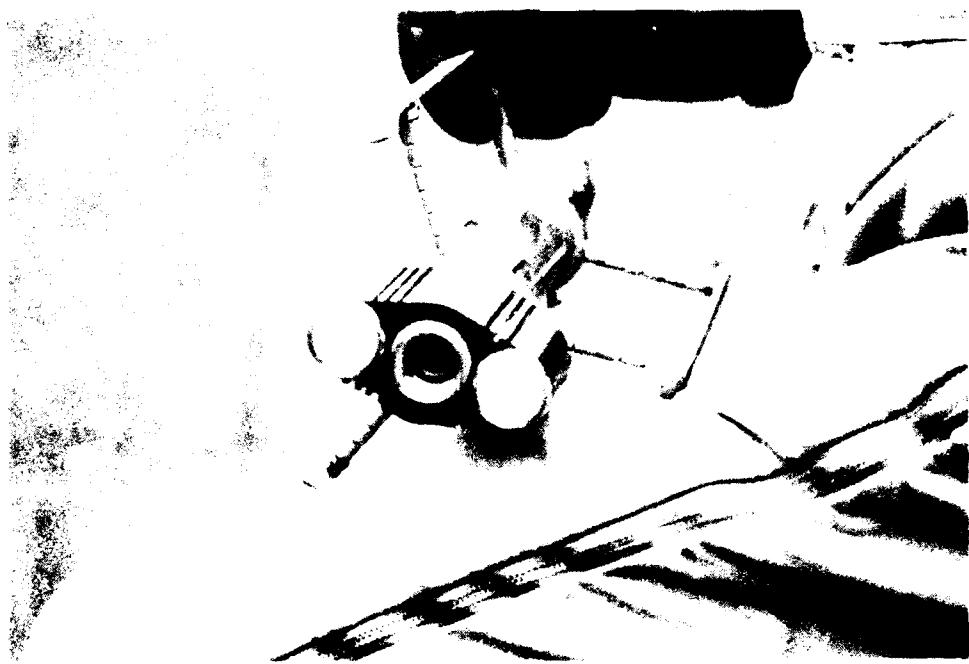


Figure 14. Downhole viewing head for downhole videocamera

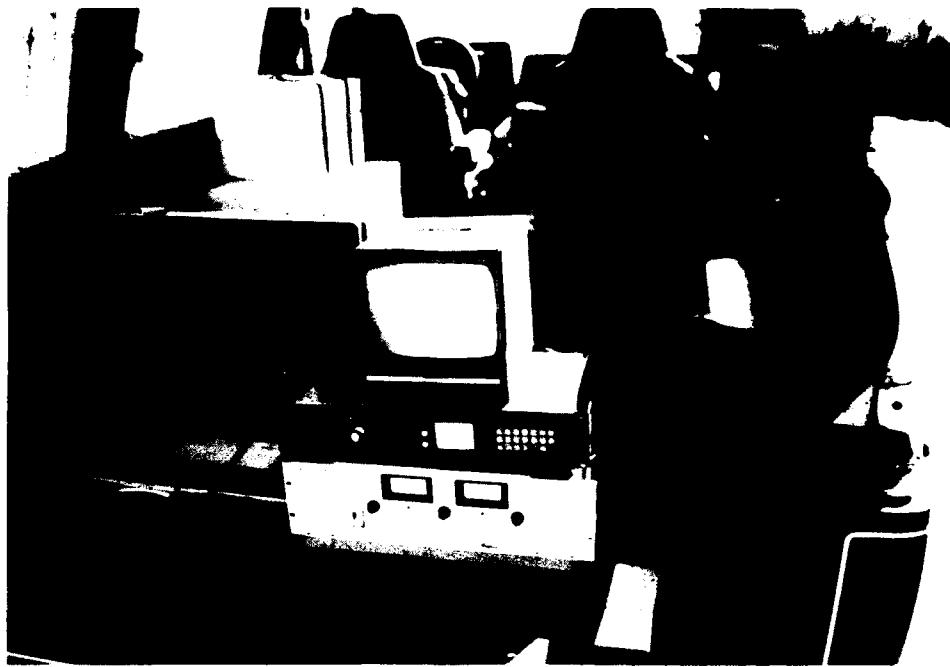


Figure 15. Downhole videocamera setup

In general, the well screens appeared in good to very good condition, particularly in light of their age. Some wells showed clogging of the screen by debris or mineralization before treatment, but upon reexamination after treatment, the screens appeared substantially open. Only a portion of the well is visible when using the side-looking camera inspection, and the filter pack was only visible in a small percentage of the videotape. The evaluation of the filter material with regard to biofouling or mineralization is not possible using visual examination.

## Downhole Videocamera Inspection During Phase 2 Development

Additional videocamera inspection was performed on wells to evaluate the effects of the BCHT treatment used during first demonstration and following second phase work. The specific wells examined were those four wells found to be obstructed and the two wells treated by ARCC, Inc. The two demonstration wells treated by the BCHT method were examined before and after that treatment.

The four wells found to be obstructed (Nos. 37, 37X, 41X, and 42) appeared to be blocked by four different means. Well 37 is obstructed at a depth of approximately 8 ft by what appears to be a restriction composed partially of wood or straw fibers in a hard, possibly asphaltic matrix, attached

to the well riser (Figure 16). This obstruction is very close to the static water level in the well. It is possible that this is the result of some kind of asphaltic compound floating on the surface of the well water hardened with grass, straw, or wood fibers accumulated in the mass. Well 37X appears to be obstructed by a somewhat sharp flat metal projection from the side of the well riser at a depth of 16 ft (Figure 17). No examination of these two wells was possible below the obstructions.

The inside diameter of Well 41X is restricted from a depth of 12 ft to the bottom of the well. The restriction appears to be the result of a smaller diameter well screen (6 in. ID) installed in the well from this depth (Figure 18) to the bottom. There is no indication that this is a liner inside the original screen, as the slots are obstructed by debris. There are no records indicating that this well was constructed differently from the others, nor is there any record of the placement of a liner within any of the wells for any reason. Other than the clogging of the well screen that is assumed to be fairly typical prior to redevelopment (shown in Figure 19), there does not appear to be any significant damage to the well screen.

Well 42 is partially obstructed at a depth of 15 ft by fragmented wood splinters from the well riser extending inward. The well screen appeared to be clogged by bacterial debris and possibly mineralization in the portion that could be examined. This is not surprising, as the obstruction prevented any redevelopment efforts in this well. A concrete fragment was detected at a depth of 45 ft (Figure 20), beyond which the camera could not pass. It is

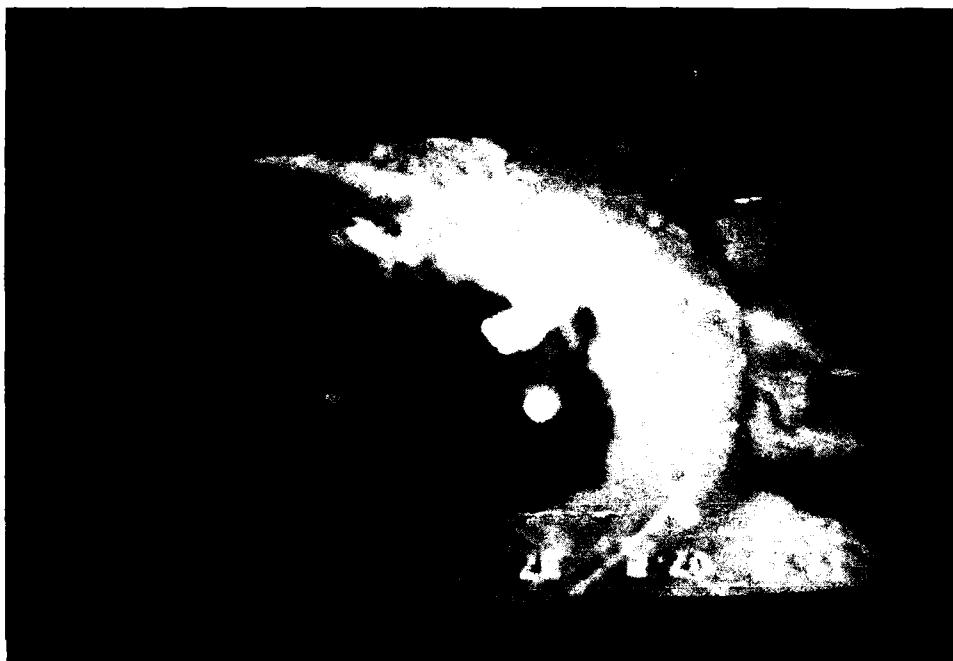


Figure 16. Obstruction of Well 37

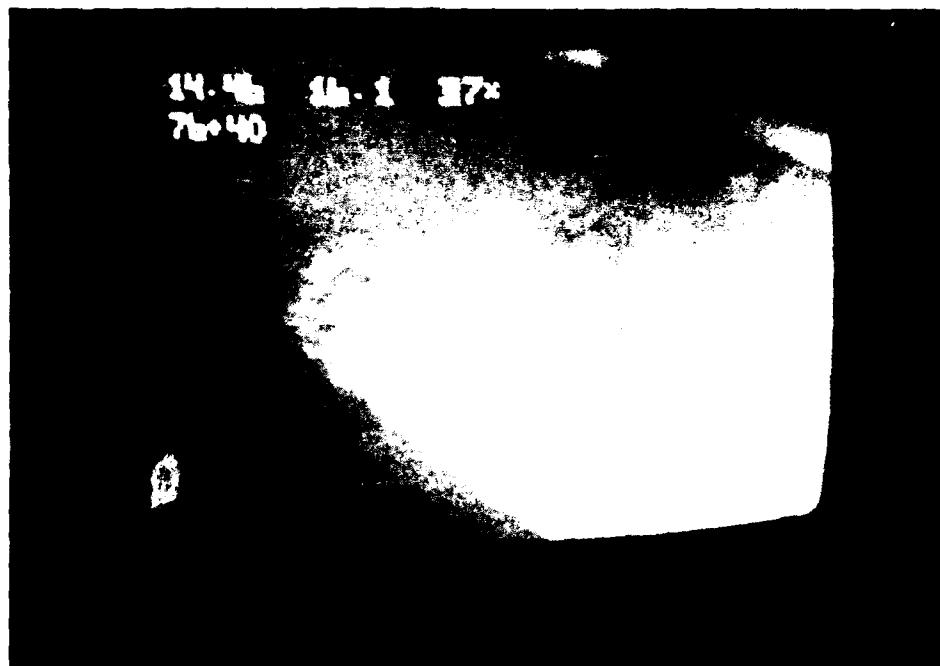


Figure 17. Obstruction of Well 37X



Figure 18. Restriction of Well 41X

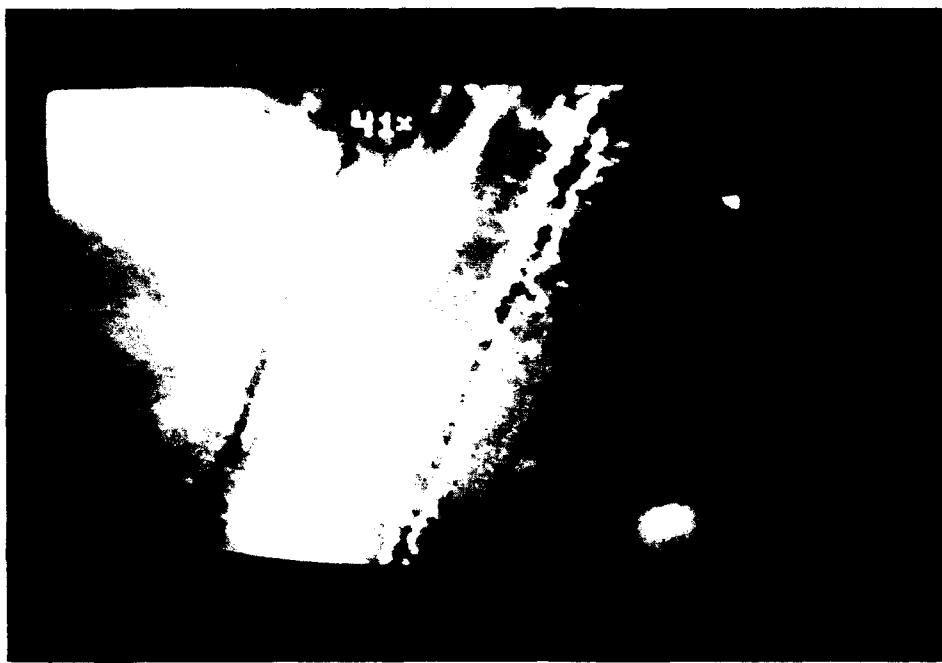


Figure 19. Well screen in Well 41X below restriction



Figure 20. Obstruction in Well 42

assumed that the well was vandalized and that the concrete fragment damaged the well riser at 15 ft as it passed down the well before becoming lodged at 45 ft.

The examination of the two demonstration wells treated by the BCHT method following the Corps' first phase redevelopment efforts showed minor amounts of bacterial debris remaining in the screen slots, primarily at the ends of the slots, with only a few slots completely blocked. Following the BCHT treatment, the well screens appeared to be much cleaner and open, as shown in Figure 21.



Figure 21. Clean well screen after redevelopment with BCHT

## Downhole Videocamera Inspection Following Phase 2 Redevelopment

Five wells were examined following the second phase of redevelopment. Well 21 was designated for inspection because it produced significant amounts of coarse sand and fine gravel during surging and pumping. Well 30 showed no significant improvement in spite of extensive second phase redevelopment efforts and was also inspected. Well 36 was inspected as a supplement to the extensive records already compiled on this well. Well 44X and 46 were inspected to compare their appearance following second phase redevelopment with that following first phase procedures and to see what, if any, long-term effects of the BCHT methods used during the first phase treatment could be seen.

There appeared to be no significant abnormalities in the wells examined following the second phase redevelopment, with the exception of Well 21, which appeared to be damaged at the bottom of the well screen (Figure 22). Some of the laths of the bottom section of screen appear to have collapsed inward, allowing filter material into the well. Careful monitoring of surging rates and procedures make it unlikely that this damage occurred during redevelopment. It is possible that the screen may have been damaged during installation and that the inward pressure produced during surging resulted in opening the screen enough to allow filter material into the well.

No other damage from any of the redevelopment procedures used on this project was noted in any of the wells examined with the downhole video camera.



Figure 22. Damage to bottom of well screen in Well 21

# 5 Results

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## Correction of Specific Capacity Values

The calculation of specific capacity for each test was done by dividing the discharge (Q) by the corrected drawdown (s). The corrected drawdown was obtained by subtracting the well loss,  $H_w$ , derived from the plot of head loss versus well discharge contained in the design document of the wells (Figure 23) from the measured drawdown (s). This adjustment allows comparison between tests performed at different discharge rates.

It should be noted that the total well loss,  $H_w$ , is the result of several components, the most significant of which is well loss through the filter and well screen at the discharge rates used in these tests. It is assumed that some form of clogging within the well filter and screen (fine particle infiltration and/or biofouling) is primarily responsible for the decline in well performance. If this is the case, then the values for well loss used to correct the results of these tests (and all previous tests) are in all likelihood too small. The effect of clogging on well loss is probably specific to each well, as screen lengths, slot spacing, filter gradation, and previous development all may differ from well to well. The correction to the specific capacities is made in this work using the available plot, with the understanding that the correction is probably slightly smaller than it should be.

The comparison of specific capacities is complicated by the variation in aquifer condition from confined to unconfined or semiconfined. The specific capacity in a well in a confined aquifer (i.e., where the groundwater level is above the upper boundary of the aquifer) is limited by the compressibility of water, which is very small, and the hydraulic conductivity of the formation. The dewatered condition that results during the drier periods in the study area or during periods of prolonged pumping of the nearby dewatering wells at Melvin Price Locks and Dam has the effect of changing the aquifer to an unconfined state. Under these conditions, the specific capacity of wells is controlled by the hydraulic conductivity and gravity. Under unconfined conditions, the specific capacity of the well is generally higher than under confined conditions. Some of the tests were conducted when the groundwater level was close to the upper boundary of the aquifer, and the state of the aquifer changed

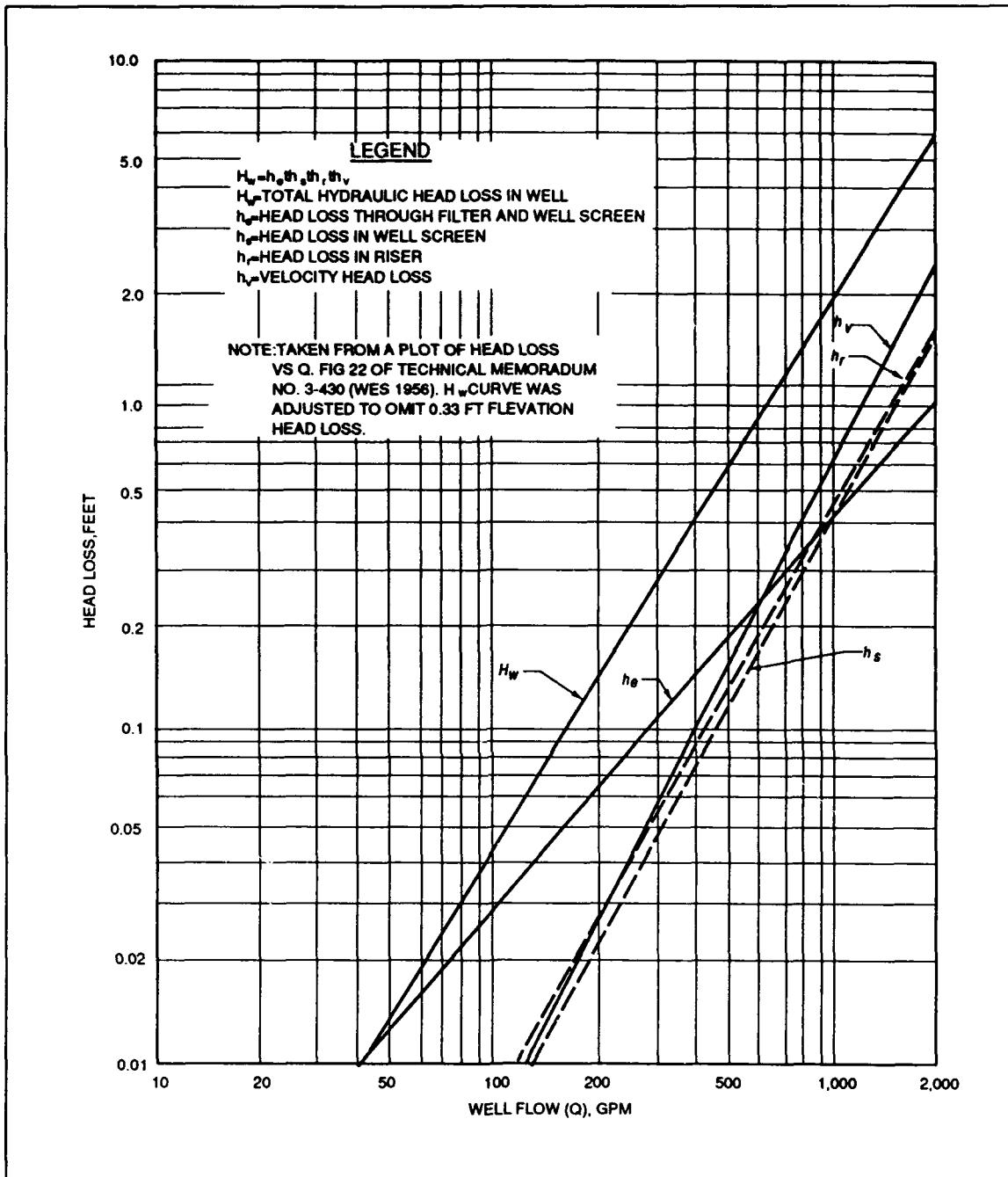


Figure 23. Plot of well losses for Wood Stave relief wells

from confined to unconfined during the course of the pump test. Other pump tests were performed during periods when the aquifer was behaving as strictly confined or strictly unconfined, or on wells located in areas where the upper confining layer is discontinuous.

It became apparent in the course of the work that a means of evaluating the progress of redevelopment and comparing the results of the different procedures used was essential. Variables which directly affect calculations of well specific capacities are the river stages during the project and the nonhomogeneity of the deltaic aquifer and are shown in Appendix E. Because each of the wells had the potential for so many variables influencing the precise comparison of test results (aquifer thickness, screen length, slot spacing, discharge rate, groundwater elevation and resultant aquifer state, head differential from well to pump, etc.), it was not practical to derive a separate set of calculations for each well and try to compare them to each other directly.

Because of the wide range of values for specific capacities from both installation tests and the tests of this program, it is useful to refer to results in terms of the percentages of some reference specific capacity for each well. The installation specific capacities ranged from 84 gal/min/ft to a high of 397 gal/min/ft. Thus a gain or loss of 20 gal/min/ft, for example, would not be nearly as significant in the case of a well with the higher specific capacity than the case of a well with a low specific capacity. It is therefore more descriptive to refer to percentages of reference specific capacities as used in this report. Because the actual groundwater elevations during the second phase BCHT redevelopment were very close to those at the time of installation, some direct comparison between those two sets of test data may be possible.

For the analysis done in connection with this work, test results from each well were converted to percentages of the *installation specific capacity* for that well. Well improvements during the first phase redevelopment were also converted to percentages of their respective *Phase 1 1987 initial* (pretreatment) test values. Well improvements during the second phase redevelopment were also converted to percentages of their respective *Phase 2 1989 initial* (pretreatment) test values. Likewise, third phase well improvements were converted to percentages of *Phase 3 1989 initial* (pretreatment) specific capacities. Bar graphs illustrating the results of pump tests before and after each phase of work are contained in Appendix E. A summary of these results follows.

## Phase 1 Results

### Initial pump test results

Initial test results indicate a decline in specific capacity compared with installation test data. Groundwater levels during the first phase of work were higher than at the time of installation. Because of this change, the specific capacities during the first phase may be lower than the installation results by approximately 25 percent (for the reasons related to the discussion of confined/unconfined conditions) in addition to any decline in well efficiency. The apparent amount of decline varied greatly from just under 10 to 67 percent of installation specific capacity, indicating that the wells responded differently to whatever factors caused the decline. The initial Phase 1 pump tests showed

the wells to have an average specific capacity of 85 gal/min/ft, with a range of values between 42 and 148 gal/min/ft, and a standard deviation of 27 gal/min/ft.

Most of the wells were given one or more intermediate tests to evaluate the effectiveness of the redevelopment procedures. As the program continued, it became evident that the initial treatment was usually not sufficient to reach the desired level of performance, and the intermediate tests were deleted from the procedures to save time.

### **Final test results**

Following redevelopment, final pump test results showed the wells to have an average specific capacity of 106 gal/min/ft, with a range of values between 62 and 173 gal/min/ft, and a standard deviation of 26 gal/min/ft.

The mean percent improvement in percent of Phase 1 initial specific capacity for the wells is 29 percent, with a standard deviation of 19 percent.

### **Well water analysis during Phase 1**

The results of the tests of the pre-first phase samples were fairly inconclusive. Two of the wells, Nos. 18 and 37, showed no evidence of stratification or biofouling. There was no ferrous iron detected in either of these wells. The third well, No. 97, had a high concentration of ferrous iron, colony-forming bacteria, and SRB. Well 97 was not included in the redevelopment project described in this report.

Evidence from the tests of the pre-BCHT demonstration samples indicated that the well water contains high concentrations of pseudomonas bacteria (probably in excess of 100,000/100 ml), moderate levels of SRB (50,000 to 100,000/100 ml) and moderate to high iron-related bacteria content (greater than 100,000/100 ml). These values are of particular significance considering the fact that they were obtained from wells that had been treated with HTH as part of the St. Louis District's redevelopment work less than 2 weeks prior to sampling.

## **Phase 2 Results**

### **Initial pump test results**

Initial pump test results in January 1989 for the second phase redevelopment indicated an apparent improvement from the conditions at the end of the first phase. The intention was to redevelop wells not yet performing at 80 percent of their installation specific capacity; however, the tests indicated that only 7 of the 32 wells treated in the first phase were below this criterion.

After reviewing the data, it was realized that the groundwater levels in January 1989 were very close to those at the time of installation, but 5 to 6 ft below those of 1987 (first phase). This led to the conclusions that the installation data were not directly correlative with first phase data, but possibly were correlative with second phase test data (for the reasons related to change in aquifer conditions discussed above).

Twenty-eight wells were redeveloped using BCHT methods in the second phase. Initial second phase tests showed the wells to have an average specific capacity of 133 gal/min/ft with a range of values from 69 to 234, and a standard deviation of 39 gal/min/ft.

### **Final pump test results**

Following BCHT redevelopment, no wells tested below 70 percent of their installation specific capacity (assuming a correlation between Phase 2 and installation data is possible). The final Phase 2 tests showed the wells to have an average specific capacity of 147 gal/min/ft, with a range of values from 80 to 229 and a standard deviation of 33 gal/min/ft. The Phase 2 efforts produced an average improvement of 21 percent relative to the initial Phase 2 test results, with a range of values from 0 to 111 percent and a standard deviation of 20 percent.

### **Well water analysis during Phase 2**

Results of testing done in January 1989 prior to the second phase BCHT redevelopment indicated a pH range from 7.2 to 7.8, and redox potentials from -40 to 220 mV. The wells that were tested at different depths showed stratification in bacterial population and chemistry, with the samples from greater depths showing greater concentrations of IRB, SRB, and other related bacteria. The populations of bacteria present are consistent with a high potential for "biofouling." The results of this testing are contained in Appendix D, along with the report of findings.

BART testing performed during the second phase BCHT redevelopment agreed in general with the findings of significant populations of IRBs and SRBs. Testing done during the BCHT is not as quantitative as that performed by Dr. Mikell, and no numbers are presented here from the BARTs.

## **Phase 3 Results**

### **Initial pump test results**

Phase 3 began with the pump testing of 59 wells. Of those, 41 were selected for redevelopment. The initial results of Phase 3 testing showed these

wells to have an average specific capacity of 76 gal/min/ft, with a range of values from 45 to 117 gal/min/ft and a standard deviation of 23 gal/min/ft. Water levels in the wells during Phase 3 were below those at the time of installation due to the drought cycle that had affected the region during the two prior years.

### **Final pump test results**

The pump tests following the Phase 3 redevelopment efforts (standard procedure using TSP and HTH) showed results that were very different from those of the earlier work. The tests indicated that 18 of the 41 wells either did not improve or actually decreased in performance as a result of the work. The average specific capacity of the wells following Phase 3 redevelopment was 78 gal/min/ft compared with 76 gal/min/ft as an initial average. The results of the final Phase 3 tests ranged in values from 51 to 137 gal/min/ft with a standard deviation of 21 gal/min/ft. The change in performance as a percentage of initial Phase 3 specific capacity had an average of +4 percent and ranged from -25 to 55 percent with a standard deviation of 16 percent.

## 6 Conclusions and Recommendations

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### Condition of Underseepage Controls

The overall condition of the levees, piezometers, berms, and relief wells appears to be good. The levee is well maintained by the Wood River Drainage and Levee District, and with the exception of some of the piezometers being damaged or missing, the underseepage controls seem to be in good condition also. A survey of the wells in the District found only six wells to be obstructed or damaged to the extent that they could not be treated. Observations during periods of high water have indicated that the relief wells, for the most part, flow when expected. The dewatering activity at Melvin Price Locks and Dam has affected the wells adjacent to the construction site to the extent that they did not flow during high-water periods of 1986.

The observation that the specific capacities of these wells decline with time is consistent with earlier observations. The amount of decline within the District varied greatly, and no single explanation for this observation is proposed here. The variation in declines in installation specific capacities is probably due to a combination of factors including biofouling, stratigraphic variability, siltation of well filter material, variation in slot spacing and screen length, impact of dewatering on the wells and surrounding aquifer, variations in amount of development at installation from well to well, and mineralization of well screens. The results of the biochemical analysis indicate that biofouling is probably the most significant contributor to the decline in effectiveness in the wells. However, the dominant bacterial genera at work vary somewhat from well to well, and the concentrations do not seem to directly correlate with the amount of decline.

### Effectiveness of Procedures

The procedural changes made during the course of the work eliminated ineffective elements of the treatment and improved the effectiveness of the

methods used. Several general observations regarding procedures have resulted from this work:

- a. The initial addition of TSP and HTM to the wells is of some benefit. The second addition of these chemicals may be of lesser benefit and requires an additional waiting period of approximately 24 hr to be of any benefit at all. Because of this time factor, it may be more efficient to delete the second chemical treatment in favor of more effective measures. The chemical additions used in the ARCC process had the added impact of heat, which increased their effectiveness. The low pH of the ARCC polymer/acid compound also is assumed to have been a significant factor in the success of that part of the program.
- b. The results of the tests show that surging appears to have the most beneficial effect upon the wells: the greater the amount of surging, the more improvement in the well. The relationship between the amount of surging and the percentage of improvement is not linear, and the amount of improvement per cycle of surging tends to decline as more surging is done. The addition of chemicals prior to surging increases the effectiveness of surging by disrupting bacterial populations in the system and separating debris from the filter material. The amount of improvement per unit of effort appears to vary greatly from well to well. It is believed that the amount of surging should be considered of primary importance in any future work of this kind.
- c. Observation of the water levels in adjacent wells during surging confirmed the lateral effect of surging. Water levels in adjacent wells began oscillating (less than 0.1 in.) shortly after surging began, with a frequency roughly the same as that of the surging.
- d. The rate of surging did not appear to be as significant as the amount of surging; however, since an increased rate of travel will result in less time expended per cycle, the rate should be increased within safe guidelines. The rate of surging was increased to nearly 5.5 ft/sec on one well, and a small amount of very coarse sand and fine gravel was noted in the infiltrate, indicating that this was slightly excessive. A rate closer to 2 to 3 ft/sec was effective and showed no evidence of damage to the wells. The use of more vigorous surging rates was not regarded as appropriate for this work because of the high risk of damage to the system.
- e. The BCHT redevelopment methods were effective and relatively time efficient. The two wells treated with these methods, Nos. 44X and 46, improved from 69 to 83 percent and from 58 to 70 percent of their installation specific capacity, respectively. These results are regarded as significantly successful, particularly considering the fact that these wells had already reached an assumed point of diminishing return with respect to redevelopment effort using the more conventional treatments. The method has the advantage of providing a certain amount

of diagnostic testing that was not included in the Corps methods. The chemical treatment used by ARCC is believed to be more effective because of the heating process and the nature of the chemicals themselves. The methods were conducted by ARCC using largely prototype equipment, and it is safe to assume that the process will improve as equipment and technique are refined.

- f. The significant populations of deleterious bacteria in the wells treated by ARCC indicate that the chemical agents used by the Corps were of only short-term impact on bacteria populations. Water samples taken later will be used to evaluate the long-term effectiveness of ARCC's chemicals. The results of both the BCHT and previous well water analysis reinforce the conclusion that biofouling is a primary factor in the decline in well performance.

## General Observations

The marginal success of the third phase redevelopment (standard procedure) may be due to several considerations. The wells in this group were influenced profoundly by two periods of dewatering for months on end. It is possible that those wells showing a decrease in performance following redevelopment attempts are in fact those that experienced the greatest impact from dewatering. The water levels in these wells were depressed to the extent that a significant percentage of the well screens were exposed to air in a moist condition. This may have caused damage to the well screens that is not easily seen using the downhole videocamera. The drastic change in water level may also have caused the phenomenon referred to as "bacterial bloom" to occur not only locally in the filter pack around wells, but within the aquifer. Surging and intermittent pumping of the wells may have actually concentrated the bacterial residue adjacent to the wells in some cases, causing the significant decline in performance observed in some wells following redevelopment efforts.

The amount of variation in test results and effectiveness of redevelopment measures is consistent with the variation of installation test data. As noted earlier, the variation is in all likelihood the result of a combination of many factors which cannot be practically evaluated within the scope of this work. The ability to change methods to accommodate this variability during the course of this work was a very important factor in the results of the program.

## Regulatory Considerations

An additional and very important consideration has developed as a result of this work. Some State agencies have interpreted the pump testing of wells and the discharge of effluent at the surface as an activity requiring permitting under the Clean Water Act.

The pumping of chemicals into an aquifer may also require a permit, depending upon the interpretation of the agencies with jurisdiction. It was suggested by the Illinois Environmental Protection Agency that even the use of a tank to collect sediment portions of effluent for evaluation may require a permit, as such a device may be considered a "treatment facility to remove suspended solids." In today's environmentally conscious atmosphere, each remediation project will be site specific and will require the project manager to prepare an exact scope of work including groundwater chemical analysis, expected chemical use, expected discharge concentration, and point of discharge. The project time table should allow for obtaining permits. Phases 1 and 2 did not require permits because of the research designation and dilution factors of the chemicals, but Phase 3 did require agency approval (not permits) and was completed under an "exemption."

## Costs

The Phase 1 wells redeveloped by the St. Louis District were done so using personnel of the Core Drill Unit at a weekly rate of approximately \$6,300, which included the use of Corps equipment and related overhead. Including delays for weather and equipment maintenance, Corps efforts were able to redevelop two to three wells/week. This translates to an approximate cost of \$2,500/well.

The second phase BCHT work was performed under a contract administered by WES at an approximate cost of \$78,000, not including the costs related to pump testing and surging that was done by Corps personnel. The total cost including Corps personnel and equipment was approximately \$120,000 for 28 wells, or approximately \$4,300/well. This included costs for time delays due to equipment breakdown and weather. The contract under which the Phase 2 work was done was not required to be a "union" contract because of the research nature of the program. ARCC, Inc., is not currently operating as a "union" contractor, and the costs of additional work will be much higher if union labor is required. It is uncertain whether or not future work of this nature can be accomplished without labor union involvement.

The Phase 3 wells were pump tested and treated at a cost of \$5,400/well under the much larger Third Stage Cofferdam Contract of Melvin Price Locks and Dam. The larger contract absorbed much of the mobilization and demobilization costs that might be included in a contract dealing only with well redevelopment; however, this part of the contract was subcontracted, the expense of which may have more than compensated for the mobilization/demobilization savings.

To realistically compare the costs of the methods used to redevelop wells at this site, consideration should be given to several factors. The St. Louis District's efforts were largely experimental at the beginning of the project. Familiarity with equipment, procedures, and logistics improved cost efficiency as work progressed. The BCHT methods were applied with prototype equipment

which had not been in use long enough to establish the life expectancy of some components in contact with corrosive chemicals and high temperatures and pressures. The experiences of projects such as this one will assist in the development of refinements in the equipment and reduction of the cost per well. Consideration should also be given to the fact that the BCHT methods were significantly successful after previous efforts had reached the assumed point of diminishing returns using more conventional procedures. None of these costs include consideration of the time and expense of the permitting requirements mentioned previously.

## Recommendations

An in-depth evaluation of the relief wells within the District is necessary to determine the needs for further underseepage controls. The initial expectation that all of the wells could be brought to 80 percent of their installation corrected specific capacities with the "conventional" set of procedures used now seems less than likely. It appears more likely that a regimen of treatment based upon the procedures described herein, possibly incorporating the BCHT methods, will result in the required redevelopment. The set of procedures used should include contingencies for wells that do not respond significantly to the initial redevelopment efforts.

As discussed earlier, the studies of relief well performance following the Flood of 1973 indicated that prolonged periods of flow substantially restored well capacity. It is possible that the flow resulting from the raising of the river stage upstream of Melvin Price Locks and Dam will have a similar effect. Any further underseepage control measures should be designed with this possibility in mind. A prolonged (5 to 10 day) pump test may be considered to evaluate the amount of redevelopment that will result from the increase in underseepage.

The installation of more piezometers to evaluate the performance of the wells in lowering the groundwater level in the area landside of the levee is planned, as well as the continued monitoring of the overall groundwater conditions of the area.

Of the methods used during the course of this work, the BCHT appears to be the most effective in restoring lost well capacity. The BCHT methods differ from those initially used by the Corps in the use of gaseous chlorine, sulfamic acid, polymeric dispersing agents, and steam heat. The surging and pump testing operations were essentially identical between the two methods. The components of the treatment combined with the diagnostic information derived from the field test kits and the indication that the methods are able to achieve results beyond the previous assumed point of diminishing returns are the basis of this conclusion.

## Epilogue

The stage of the Mississippi River at Alton was raised, and the operation of Melvin Price Locks and Dam began early in 1990. The construction of the second lock and remaining portion of the dam is in progress. Following the raising of pool to the design elevation of 419 ft, many of the relief wells upstream of Well 36X began flowing. These are wells that were treated in Phases 1 and 2. No flow was observed in the wells treated in Phase 3 until the high-water (near-flood) period of June 1990. This fact and the response of these wells to redevelopment are cause for further investigation. Additional piezometer installation is planned as a means of monitoring the effects of the rise in pool and the performance of the wells. An evaluation of the long-term performance of these wells will not be possible until dewatering associated with the final stage of construction of Melvin Price Locks and Dam is complete.

A pilot program for redevelopment of 60 wells in the Metro East Sanitary and Drainage District (located downstream of the Wood River Drainage and Levee District and directly across the Mississippi River from St. Louis) was conducted from December 1989 through February 1990. These wells are of identical construction to those in the Wood River program. Treatment consisted of an initial pump test, 2 hr of surging at the same rates used at Wood River, removal of infiltrate where necessary, and a final pump test. No chemical additives were used. Preliminary evaluation of the results indicated only minor improvements in well performance. This reinforces the evidence that some type of chemical additives are important contributors to redevelopment.

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# **Appendix A**

## **Blended Chemical Heat Treatment Patent**

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United States Patent (19)

Rogers et al.

(11) Patent Number: 4,765,410

(45) Date of Patent: Aug. 23, 1988

[54] METHOD AND APPARATUS FOR  
CLEANING WELLS

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[21] Appl. No.: 65,916

[22] Filed: Jun. 24, 1987

[51] Int. Cl. 4 E21B 43/27

[52] U.S. Cl. 166/303; 166/357;

166/312

[58] Field of Search 166/303, 307, 309, 57

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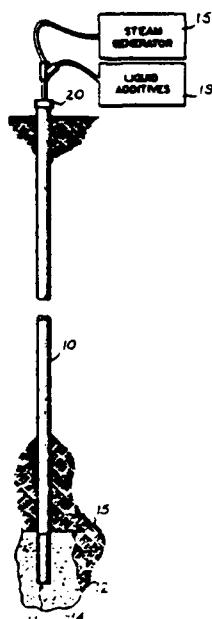
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[57] ABSTRACT

A method and apparatus for cleaning a well wherein chemicals are applied to the well screen with steam. The well screen may be first washed with a sterilizing agent, and subsequently a chemical mix is added to the steam. The chemical mix includes a sterilizing agent, an acid, and perhaps a surfactant. The well is capped during treatment so the well becomes pressurized; and, the chemical mix is forced out beyond the well screen. The surfactant aids in penetrating the clog, while the sterilizing agent kills any plant or animal life that is causing or contributing to the clog. Some sterilizing agent may remain to prevent regrowth of life forms that may feed on other chemical components. The well may be surged to assist further in breaking up the mass clogging the well.

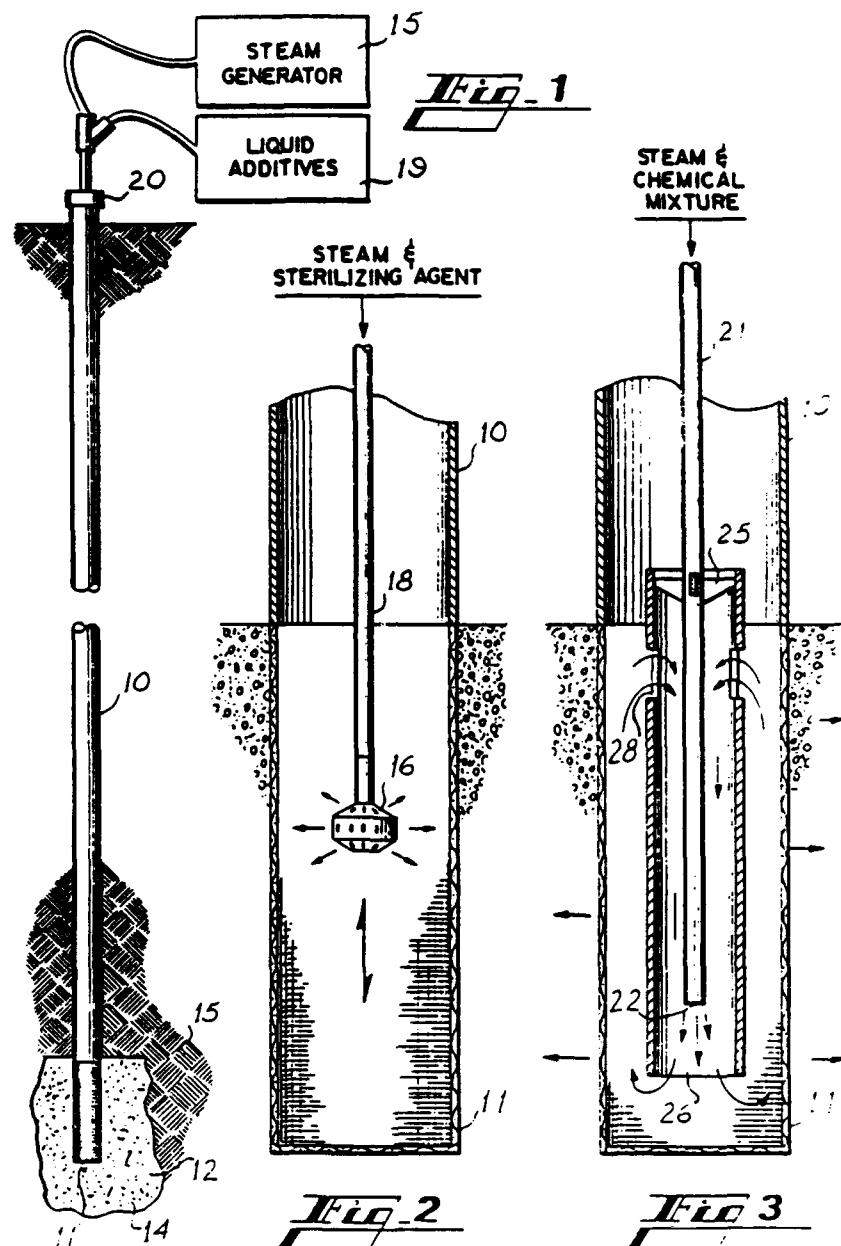
14 Claims, 1 Drawing Sheet



U.S. Patent

Aug. 23, 1988

4,765,410



### METHOD AND APPARATUS FOR CLEANING WELLS

#### INFORMATION DISCLOSURE STATEMENT

It is known that many wells become clogged so that liquid does not easily flow to or from the well. It is also known that, in some of these wells, bacteria form a mass that, at least partially, blocks the flow. However, there is usually an assumption that any bacterial blockage is in conjunction with other materials such as paraffin, clay, various chemical precipitates such as carbonates and the like.

The prior art methods and apparatus for cleaning wells have usually taken the form of a solution pumped or otherwise discharged into the well. The solutions have included chlorine-bearing liquids such as sodium hypochlorite to kill bacteria, and have included alkaline salts. Sometimes the solutions have been heated, especially for meltable substances such as paraffin. U.S. Pat. No. 3,482,636 to Crowe, for example, discloses a method for cleaning a well that is blocked by a combination of bacterial slimes, algae and synthetic polymers. The method includes the use of a hypohalite, such as sodium hypochlorite, mixed with an alkali, such as sodium hydroxide, to solubilize material and open the pores in the earth surrounding the well, the hypohalite being followed by an acid, such as hydrochloric acid. This patent relies on the assumption that the blockage is a mixture of several substances, and relies very heavily on the chemical action to remove the blockage.

In spite of patents such as the above mentioned Crowe patent, there is no known method for opening wells such as water wells, relief wells, injection wells and the like, and maintaining the wells open for an extended period of time. The prior art systems result in only partial opening in the first place, and the wells tend to reclog very soon.

#### SUMMARY OF THE INVENTION

This invention relates generally to a method and apparatus for cleaning wells, and is more particularly concerned with a method and apparatus for destroying a bacterial coating causing occlusion of a well.

The present invention provides a method and apparatus for opening a well, and cleaning the well sufficiently that the well will remain open for an extended period of time. The method includes the steps of washing the well interior with a sterilizing agent for preliminary sterilization, and subsequently capping the well and injecting steam carrying a chemical mixture. The fact that the well is capped causes pressure to build up within the well and force the chemical mixture outwardly into the gravel pack around the well, and into the surrounding earth. The method therefore opens not only the immediate vicinity of the well, but also some surrounding area.

The preliminary sterilizing agent may be any of numerous materials, but a chlorine-bearing material is generally effective and safe. The chemical mixture for use with the pressurized treatment includes a sterilizing agent, and also includes an acid, and may further include a surfactant. The combination of the chemicals penetrates the material causing the clog. The heat and pressure in conjunction with the chemicals tend to dislodge the material; and, the convective currents in conjunction with the pressure cause a general flowing of the material so the material can be removed from the

site. It has been found that the well is very free-flowing after treatment, and does not show reclogging quickly, and it is thought that some chemical remains in the earth to assist in keeping the area open.

#### BRIEF DESCRIPTION OF THE DRAWINGS

These and other features and advantages of the present invention will become apparent from consideration of the following specification when taken in conjunction with the accompanying drawings in which:

FIG. 1 is a cross-sectional view of the earth showing a well being cleaned in accordance with the method of the present invention;

FIG. 2 is an enlarged cross-sectional view through the well screen area of the well shown in FIG. 1, and illustrating the preliminary sterilizing of the well; and,

FIG. 3 is a view similar to FIG. 2 showing the final chemical treatment in accordance with the present invention.

#### DETAILED DESCRIPTION OF THE EMBODIMENT

Referring now more particularly to the drawings and to that embodiment of the invention here presented by way of illustration, it will be realized that the well illustrated in FIG. 1 of the drawings is typical of a water well, but the inventive method is applicable to many forms of well. Looking at FIG. 1, however, it will be realized that the well includes a well casing 10 that is typically a steel pipe, and a screen 11 at the lower end of the well, which is again steel or the like. Most commonly, the well casing 10 and the screen 11 are galvanized steel, so that both iron and zinc are present. Since certain bacteria feed on these metals, the well provides a center for growth of several forms of bacteria.

In the examination of wells, it has been found that a mass of bacteria will grow substantially at the well screen 11. As the mass grows, it develops a polymeric covering, or skin, around the mass. Thus, in the prior art techniques of applying chlorine or other bactericides, some relatively few of the bacteria may be killed; but, the killed bacteria simply add to the covering or skin to protect the remainder of the bacteria even better.

When a well is first drilled, it should be recognized that the presence of the well allows more oxygen to the subterranean area than has previously been available. This fact in conjunction with the presence of the iron and other metals facilitates the growth of aerobic bacteria. Growth is therefore greatly enhanced whereas the growth rate may have previously been quite slow. Since the aerobic bacteria form a mass contained within a sac of a tough polymeric material, an adjacent layer may be deprived of oxygen. Rather than becoming a solution to the problem, however, the adjacent layer becomes an area of growth for anaerobic bacteria. The process may continue so that successive layers contain aerobic bacteria, than anaerobic bacteria.

From the foregoing discussion, it should be realized that the bacterial mass or coating will be attached to the well screen 11, and will extend generally throughout the gravel pack 14 which is intended to keep the area porous. The bacteria will further extend out into the surrounding earth 15, which may be the aquifer from which water is to be obtained. While the bacterial coating itself may be the initial problem, and the sustaining cause of the problem, it will be understood by those skilled in the art that the bacteria produce additional

contaminants, such as ferric oxide in the case of iron bacteria, to exacerbate the problem.

With the above in mind, attention is directed to FIG. 2 of the drawings in conjunction with FIG. 1. It is contemplated that a steam generator 15 will be used at the top side of the well to provide steam, preferably superheated to some extent as will become better understood hereinafter. The steam will be used as the carrier for other materials to be discharged into the well, the arrangement shown being in the nature of a vaaturi, though it will be understood that the liquid treatment chemicals can be pumped at a metered rate if desired. The result to be achieved is the mixing of the selected chemical with the steam for treatment of the well. Obviously too, a down-hole steam generator may be used if desired, and the method will remain the same.

The initial treatment of the well is shown in FIG. 2 wherein a barrel washer 16 is carried at the end of the supply tube 18. With the barrel washer 16 in place, the liquid additive 19 will be a sterilizing agent. The sterilizing agent is preferably a chlorine-bearing material, and solutions that have been tested include sodium hypochlorite and chlorine gas dissolved in water. With the sterilizing agent being dispensed through the supply tube 18, the tube 18 is moved vertically, reciprocally, to wash the inside of the well screen 11. During this treatment, the cap 20 on the well will be vented so the action takes place approximately at normal pressure of the well.

Use of the barrel washer as shown is not critical to the practice of the present invention, but it will be seen that the device shown will distribute the sterilizing agent very widely on the well screen 11 as the device 16 is reciprocated within the well. Other nozzle arrangements can be substituted as desired.

The preliminary sterilization shown in FIG. 2 of the drawings will tend to kill organisms that are inside the screen 11, or immediately at the exterior side of the screen. This simply prepares the well for the next, thorough, treatment, and for this treatment attention is directed to FIG. 3 of the drawings.

In FIG. 3 the supply pipe is designated at 21, and the pipe 21 is open at its lower end 22 for discharge of fluids therefrom. The pipe 21 carries a concentric member 24, the member 24 being here shown as supported from the pipe 21 by a plurality of struts 25. While the struts 25 are here shown only at the top of the member 24, it will be readily understood that additional struts or other support members may be used if required, the important feature being to allow fluid flow between the pipe 21 and the member 24.

The pipe 21 terminates within the member 24, which is to say that the fluid from the pipe 21 is discharged above the open end 26 of the member 24. Adjacent to the upper end of the member 24, there are windows 28 opening through the member 24 for allowing fluid to enter the member 24 from the within the well.

With the above described apparatus in mind, the method for use should be understandable. The steam generator 15 will be used, and the liquid additives 19 will consist of a mixture of an acid, a sterilizing agent and, if needed for the particular well, wetting agents or surfactants. This particular mix is important because of the problem to be attacked which is discussed above.

An acid is needed because one of the problems encountered is ferric oxide, and an acid attacks this substance quite well. In addition, the bulk of the material to be removed tends to be more soluble in a lower pH. The

sterilizing agent is needed as with the preliminary treatment to kill any life forms that may be present, including the bacteria that probably constitute the principal problem. Finally, the surfactant is needed in some cases to penetrate the mass causing the blockage, though in some environments the surfactant will not be required.

If the well is in an area of limestone, the surfactant may be unnecessary because the acid will attack the limestone to such an extent that the clog will be broken up because the supporting limestone will be broken up. Other particular environments may not require a surfactant, though of course the surfactant will be used in heavy clay and the like.

As was discussed above, a colony of iron bacteria or similar bacterial masses will grow and produce a polymeric covering that protects the bacteria from harm. Even treatment with rather strong doses of chlorine or other bactericides will only shock the mass and kill a small percentage of the bacteria in the mass. The covering will then become thicker and harder to penetrate. In this event, the present invention may utilize a surfactant to assist in penetrating the covering and obtaining thorough wetting of the entire bacterial mass.

Those skilled in the art will understand that sulfamic acid, or amidosulfonic acid ( $\text{H}_2\text{N}-\text{SO}_3\text{H}$ ), is known as a cleaning agent, and it has the additional advantage of tending to stabilize chlorine. Sulfamic acid is therefore the preferred acid for use in the present invention, though other acids such as oxalic or the like may be satisfactory. The sterilizing agent is preferably chlorine, especially for use in water wells since chlorine is safe for use in potable water, though other sterilizing agents may be used where human consumption is not contemplated. The surfactants used may be phosphates or any of numerous other well known surfactants, depending on the precise conditions in the well to be cleaned.

Now, with the above discussed mixture as the liquid additive 19, the steam generator 15 will be used to inject steam and carry the additive 19 into the well. In case a down-hole steam generator is used, the additives will be added to the steam within the well. The cap 20 will be in place so the well will be pressurized. As the steam is ejected from the end 22 of the pipe 21, it will be recognized that a lower pressure will be established within the member 24 above the end 22. The member 24 will be filled with fluid, so a current will be established as shown by the arrows. Fluid will move from the pipe 21, down through the open end of the member 24, and be deflected around the outside of the member 24 because of the confinement within the screen 11. Fluid will then enter the windows 28 in the member 24 and move downwardly.

Remembering that the pipe 21 supplies steam with the additives entrained therein, it will be understood that the environment will be heated by the recirculation of the fluid. Thus, as additional steam is injected into the well, the pressure increases and the temperature increases. The above named chemicals will be effective at ambient temperatures, but the activity is of course increased at elevated temperatures. The optimum range appears to be between 55° and 95° C. above ambient temperature, though success has been achieved as low as 20° C. above ambient temperature. The only upper limit is the limit of the stability of the chemicals involved, and this is beyond any practicable physical limit.

The combination of the chemical treatment with the heat and pressure will penetrate a mass clogging the

well and fragment and polymeric covering that normally protects the bacteria within the mass. Once the sterilizing agent thoroughly wets the entire mass, the bacteria will be effectively killed. Because of the pressure in the well, the chemicals will be forced outwardly, through the gravel pack 14 and somewhat out into the surrounding earth 15. The sterilizing agent will be carried out into the earth, and the residual sterilizing agent will continue to prevent bacterial growth. This is thought to contribute to the maintaining of the well for an extended period of time after the cleaning.

Even beyond the simple pressure outward, the use of a surging technique will greatly improve results. In general terms, pressure is applied and released so fluid flows out and back. This surging assists in breaking up blocking material for thorough cleaning. Tests indicate that particle sizes are smaller after surging, so reclogging will be less likely.

It will now be seen that the present invention provides a relatively simple method and apparatus for cleaning wells. While the disclosure is directed largely to water wells wherein water is withdrawn from the aquifer, the invention is equally adapted to use in relief wells, such as toe wells in dams, in recovery wells wherein a well is drilled to recover spilled material, and in injection wells wherein waste is injected into the ground for disposal. In all cases, the well must remain free and unclogged for continued use of the well, and the present invention provides a highly desirable system.

It will also be understood that the well will first be sampled to determine the particular form or forms of bacteria infecting the well, and the chemical mix will be varied to be most effective on the particular strains present.

It will therefore be understood by those skilled in the art that the particular embodiment of the invention here presented is by way of illustration only, and is meant to be in no way restrictive; therefore, numerous changes and modifications may be made, and the full use of equivalents resorted to, without departing from the spirit or scope of the invention as outlined in the appended claims.

We claim:

1. A method for opening a clogged well including the steps of placing a steam line into said well, said steam line terminating generally at the bottom of said well, adding a chemical mix into said steam line, and injecting steam with said chemical mix into said well through said steam line, continuing the step of injecting steam with said chemical mix until the temperature in said well is at least 20° C. above ambient temperature, said chemical mix comprising a sterilizing agent and an acid.

2. A method as claimed in claim 1, and further including the step of capping said well so that the said step of injecting steam into said well raises the pressure within said well.

3. A method as claimed in claim 2, and including the step of placing a sleeve around the end of said steam line, said sleeve defining openings at the upper end thereof so that fluid in said well recirculates from the lower end of said sleeve and into said openings in the upper end thereof.

4. A method as claimed in claim 3, and further including the step wherein said steam line is placed into said

well, a sterilizing agent is added to said steam, and said steam with said sterilizing agent is directed against the well screen prior to the said step of adding said chemical mix to said steam.

5. A method as claimed in claim 4, wherein the said step of directing said steam with said sterilizing agent against said well screen is carried out by reciprocating a nozzle within said well discharging said steam and sterilizing agent.

6. A method as claimed in claim 1, wherein said acid is sulfamic acid and said sterilizing agent is a chlorine-bearing material.

7. A method as claimed in claim 6, wherein said sterilizing agent is selected from the group consisting of sodium hypochlorite and chlorine gas dissolved in water.

8. A method as claimed in claim 7, wherein said chemical mix comprises 60% sulfamic acid, 40% chlorine-bearing liquid material, and a surfactant dissolved in the liquid.

9. A method as claimed in claim 8, wherein said step of injecting steam into said well is continued until the temperature is between 55° C. and 95° C. above ambient temperature.

10. A method as claimed in claim 8, wherein said step of injecting steam into said well is continued until the temperature is at least 55° C. above ambient temperature.

11. Apparatus for cleaning a well, said well including a well casing, and a well screen generally at the lower end of said well casing, said apparatus including steam generating means for providing steam generally at the area of said well screen, and a sleeve disposed adjacent to said well screen, said sleeve being generally parallel with said well screen and defining an open lower end for allowing discharge of said steam, said means for providing steam generally at the area of said well screen including a pipe within said sleeve, concentric with said sleeve and terminating adjacent to said open end of said sleeve, said sleeve defining at least one window at the upper end thereof, said sleeve being of less diameter than said well casing for allowing fluid circulation between said sleeve and said well casing.

12. Apparatus for cleaning a well, said well including a well casing, and a well screen generally at the lower end of said well casing, said apparatus including steam generating means for providing steam generally at the area of said well screen, and a sleeve disposed adjacent to said well screen, said sleeve defining an open lower end for allowing discharge of said steam, said sleeve defining at least one window at the upper end thereof, said sleeve being of less diameter than said well casing for allowing fluid circulation between said sleeve and said well casing, and further including means for adding chemicals into said steam.

13. Apparatus as claimed in claim 12, and further including capping means for closing said well casing for containing steam injected into said well casing.

14. Apparatus as claimed in claim 12, and further including a steam line for conducting said steam to said well screen, and a nozzle selectively receivable on said steam line for directing steam and chemicals against the interior of said well casing and said well screen.

\* \* \* \*

## **Appendix B**

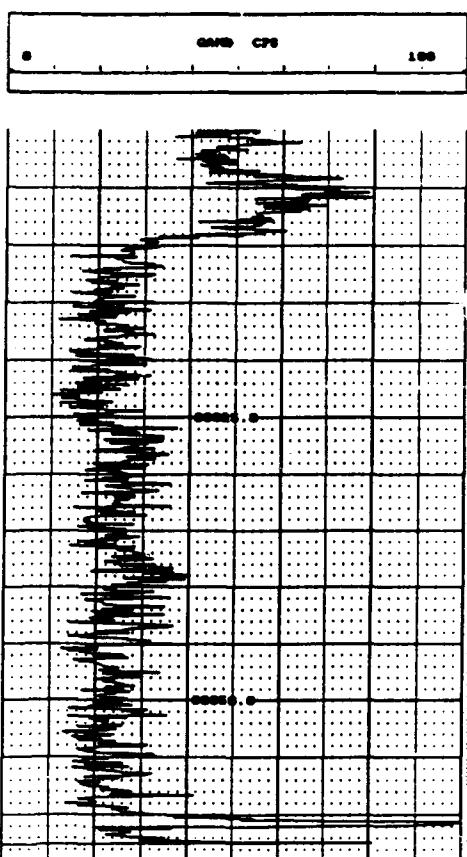
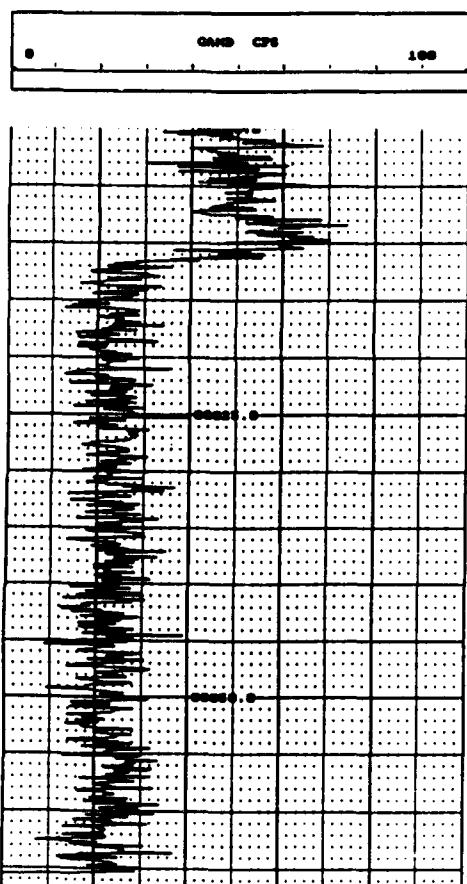
### **Natural Gamma Logs of Selected Relief Wells**

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These logs were produced using the natural gamma setting of the St. Louis District's electric logger. Natural gamma logging was selected because the results are not severely masked by well screen or risers. Wells were selected after reviewing pump test results and stratigraphic cross sections. The relatively higher gamma readings are generally indicative of clayey materials, which tend to act as aquitards or confining layers.

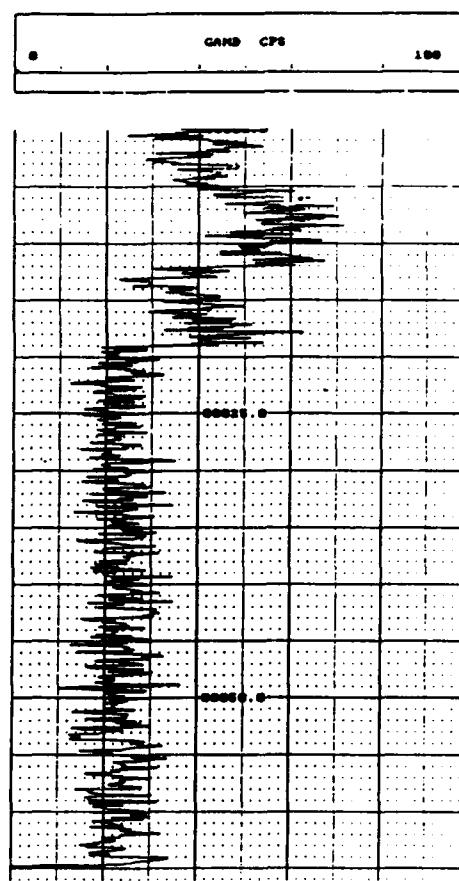
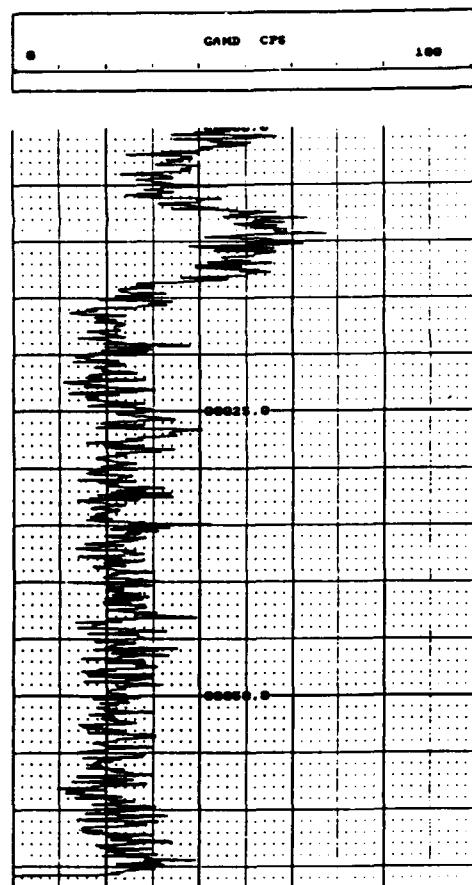
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TIME: 1500  
OPERATOR: KISSANE  
COMMENT1: DEPTH 67.1 FT.  
COMMENT2: GNL 12.3 FT.

COMPANY: USCLASSED-GG  
HOLE ID: MR-38  
LOCATION: UPPER WOOD RIV.  
DATE: 11 JUNE 1989  
TIME: 1230  
OPERATOR: KISSANE  
COMMENT1: GNL 10.4 FT.  
COMMENT2: DEPTH 64.8 FT.



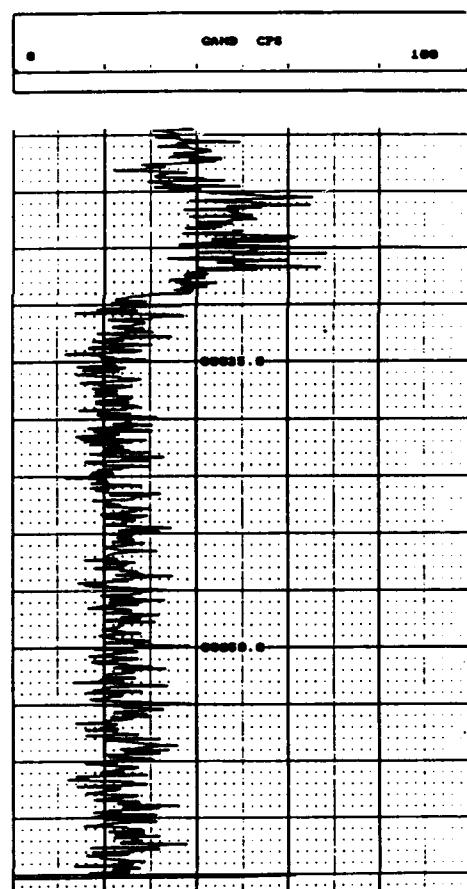
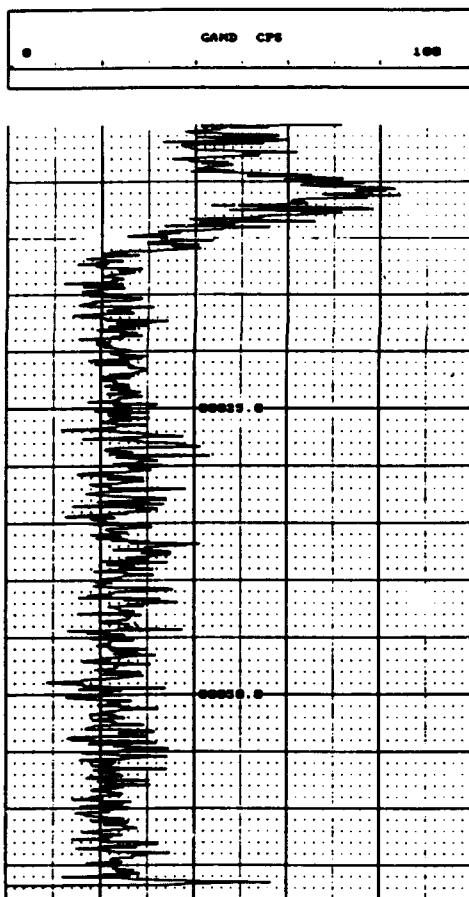
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COMPANY: USCELMSED-GG  
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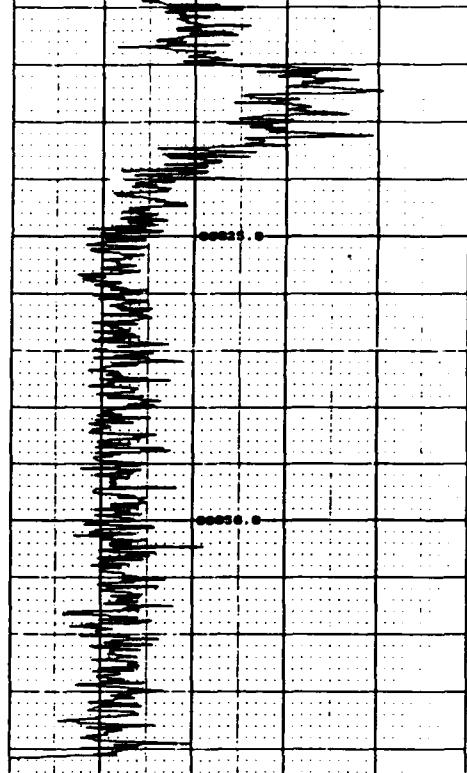
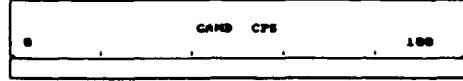
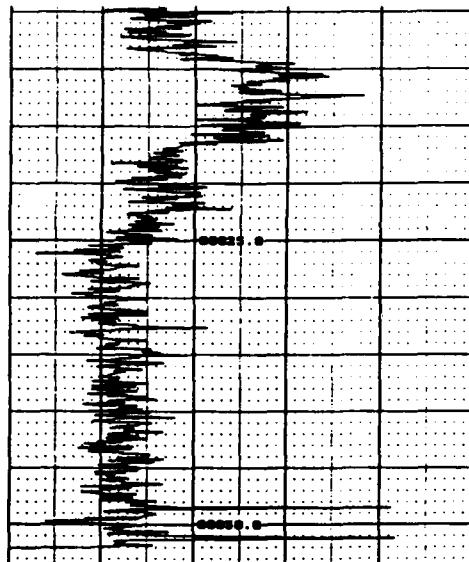
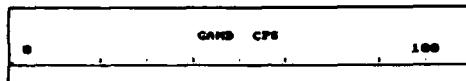
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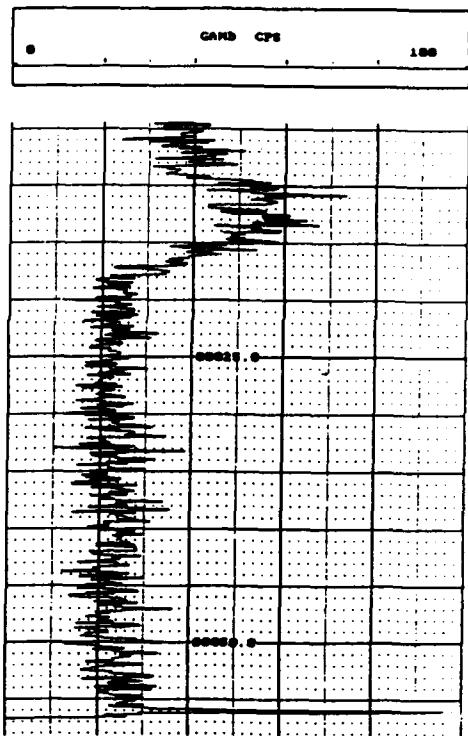
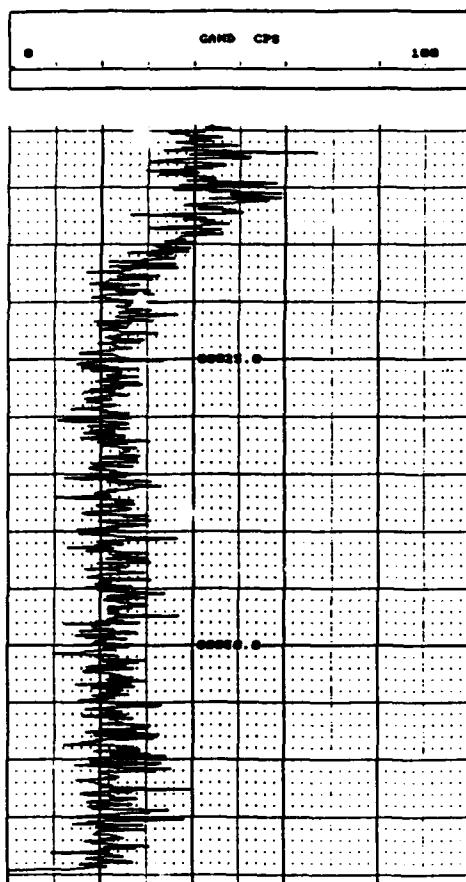
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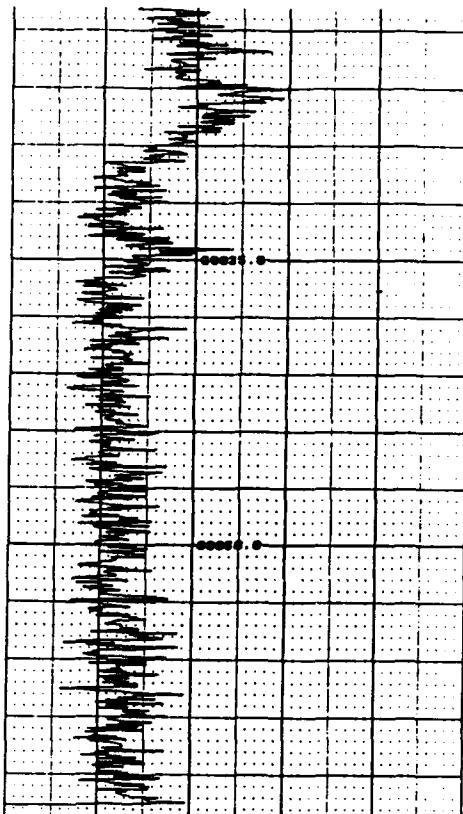
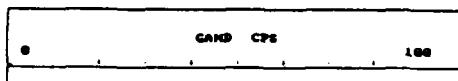
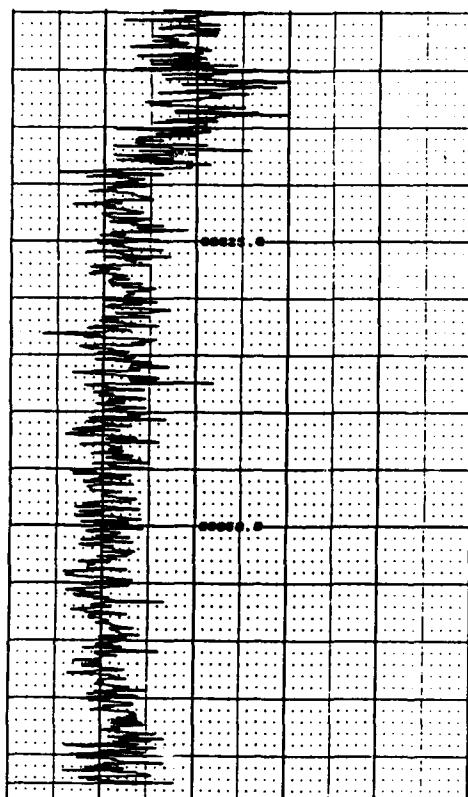
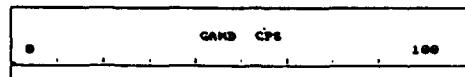
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COMMENT2: GNL 17.7 FT.

COMPANY: USCELMSED-GG  
HOLE ID: MR-46  
LOCATION: WOOD RIVER ILL  
DATE: 28 JUNE 1989  
TIME: 1100  
OPERATOR: KISSANE  
COMMENT1: DEPTH 58 FT.  
COMMENT2: GNL 17.4 FT.



COMPANY: USCELMSED-GG  
HOLE ID: WR-63  
LOCATION: WOOD RIVER ILL  
DATE: 28 JUNE 1989  
TIME: 1448  
OPERATOR: KISSANE  
COMMENT1: DEPTH 73.8 FT.  
COMMENT2: GWL 17.9 FT.

COMPANY: USCELMSED-GG  
HOLE ID: WR-84  
LOCATION: WOOD RIVER ILL  
DATE: 27 JUNE 1989  
TIME: 1500  
OPERATOR: KISSANE  
COMMENT1: DEPTH 74 FT.  
COMMENT2: GWL 18.5



# **Appendix C**

## **Biomass Development Versus Time Associated with Pumped Wells**

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### **Biomass Development Versus Time Associated with Pumped Wells<sup>1</sup>**

by

Al Mikell,<sup>2</sup> Roy Leach,<sup>3</sup> George Alford,<sup>4</sup> Richard Jack<sup>5</sup>

#### **Abstract**

This paper will present data and comments on biomass development around pumped wells versus time (approximately 1 year). Clean split-spoon sampling techniques were used to procure samples at various depths in a gravel pack and at corresponding depths in the aquifer out from the well. This routine was repeated twice during the study period.

Lipid analysis was used to demonstrate biomass development and also methods and location of accumulations as the well was pumped. The split-spoon sampling regime included sampling of the nearby sediment which was used to establish bacterial populations, densities, and community structure.

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<sup>1</sup> Reprinted from *Proceedings of the 1991 Outdoor Action Conference*, with permission from the National Ground Water Association.

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<sup>5</sup> Richard Jack, University of Tennessee, Knoxville, TN.

## Introduction

Many types of biofouling have been reported in water wells (1, 2, 3). The types of fouling are dependant on the microorganisms involved. Physical and chemical parameters control the niches available for microbial growth. Existence of and competition for these niches determine the numbers and types of microbes in the fouling community. Microbial communities are dynamic. When sufficient biomass impedes a process of human interest, biofouling has occurred, regardless of the "type" of microbial community.

To prevent, predict, or control biofouling reliably and efficiently, it is essential to understand the biofouling type. This is usually not the case as most fouling treatment is a crises management response. The types of microbes and their combinations (consortia) which participate to produce fouling are infinite. Nevertheless, their existence, life, and death are controlled by the laws of thermodynamics. Energy must be obtained by biological oxidations and resultant electrons produced must be transferred to appropriate electron acceptors. Just as all human diseases do not respond equally to one treatment, nor will all fouling types. Understanding which reactions are available to the microbes and how they interact will allow scientific treatment. Our long term goals are the development of biofouling diagnostics and treatment regimes by biological monitoring.

This initial study, conducted by the U.S. Army Engineer Waterways Experiment Station (WES), concerns the origin of biofouling in pressure relief wells at Grenada Lake, Grenada, MS. The relief wells are located at the downstream toe of the dam, to dissipate the uplift pressure beneath the toe of the dam. This dam was designed with relief wells and toe drains for pressure relief, and failure of the pressure relief systems can result in dam failure. The wells at Grenada have suffered chronic biofouling which has been thought to be caused by the presence of iron related bacteria. Several objectives are defined to examine this problem and affect solution(s).

- a. *Screen sediments at the base of Grenada Dam for iron bacteria.* Iron bacteria are a diverse lot, both genetically and with regards to their physiology. Our objective was to determine the indigenous types of iron bacteria in these sediments. The vertical and horizontal distribution of these organisms adjacent to Grenada Dam would be important in predicting the fouling potential of relief wells and drains.

Due to safety and economic reasons, it was not feasible to sample and examine sediments immediately adjacent to the pressure relief wells. We therefore obtained samples from borings surrounding an abandoned well that was within 150 ft of the design relief well system at the base of Grenada Dam. The well had not been disturbed for approximately 2 years and could be pumped without compromising the dam's safety.

b. *Determine the vertical and horizontal microbial density and community structure in sediments at the base of Grenada Dam.* Although "iron bacteria" have been deemed important, many types of bacteria participate in biofouling. To determine the numbers and types available for potential fouling, a phospholipid fatty acids (PLFA) technique was used to determine biomass and features of the microbial community. Select PLFA's are restricted to the cell membranes of certain microbes creating a biomarker for these microbes. As many organisms have not been cultured successfully, PLFA's were chosen to complement standard microbiological techniques. Organisms which may be grown are difficult to remove from sediment, but their removal is essential for accurate plate counts of colony forming units (CFU). Heterotrophic plate counts of CFU were determined after pumping, primarily to provide isolates for scientific study. The fatty acid extraction procedure allows quantitative recovery in a variety of sediment types. These attributes of the PLFA analyses overcome many shortcomings of standard techniques (4) to enumerate and define microbial populations in the environment.

c. *Determine changes in microbial vertical and horizontal distribution and community structure induced by well flow.* Crucial to the understanding of well biofouling is the relationship of flow into the well and the mechanisms of fouling. As water flows from a well, whether pumped or from artesian pressure, the horizontal velocity in the porous aquifer increases according to Darcy's law, which states that as the hydraulic gradient increases, velocity increases as flow converges toward a well. The actual velocity at any point is affected by pumping rates, aquifer characteristics, slope of the water table, and recharge sources close to the well. Attached or sessile microbes are dependant for growth on the concentrations of nutrients that they see per unit time. Therefore, in a flowing well, higher velocities are producing larger flows; thus more organisms can be supported due to the increased nutrients in the vicinity of the well. Depending on the construction of the well, oxygen, the favored electron acceptor, can diffuse from the well to the sediments. The diffusion of oxygen further complicates, but defines, the fouling geometry or interface.

This hypothesis was tested by sampling the sediment vertically to include the primary sediment types and horizontally to incorporate the logarithmic pattern. This was accomplished on Trip I, before pumping, and Trip II, after pumping the master well. Pumping was cyclic, on 6 hr and off 2 continuing for 9 weeks.

d. *Examine microbe types in select pressure relief wells.* A preliminary investigation of the types of filamentous bacteria was conducted on samples from two relief wells, Nos. 2 and 92, in the downstream toe. Prussian blue and acridine orange epifluorescent stains were used to visualize the filamentous bacteria. Scanning electron microscopy and x-ray diffraction were used to examine the filamentous bacteria and the

metal content of the sheath of *Leptothrix* sp., the predominant filamentous bacterium seen in sample relief well No. 92.

- e. *Design and evaluate treatment regimes for relief wells and horizontal drainage systems.* This is part of the current Phase II project.

## Materials and Methods

### Site description and bore hole placement

The location of sample bore holes is shown in Figure C1. These locations were chosen to obtain more samples in the aquifer nearer the master well since the velocities, flows, and oxygen diffusion would cause an increase in biological activity in this zone. Biofouling generated should reflect this.

### Sediment sampling

Before drilling commenced, the drill rod and tools were thoroughly steam-cleaned. Chlorine in the form of a commercial pool chlorinating agent was added to the drilling water at the concentration of two 3-in. tablets per tank load. The chlorinating agent contained 99-percent trichlor-s-triazinetrione. This was said to provide 89-percent available chlorine. Available chlorine in the drilling mud was measured at beyond detection limits ( $>3$  mg/l) using a simple chlorine detection kit. A reverse flow fishtail drag bit was used to drill the sample holes. The density of the sediment was such that an outer casing was not used except in the borings in close proximity to the pumped well where it was hoped that caving of the hole and chlorine contamination of adjacent samples could be minimized. A split-spoon sampling tool, thoroughly sanitized in the chlorine water, was used to obtain sediment samples. Samples were periodically checked for chlorine after removing the outer drilling mud layer. No chlorine was detected even in sediments from the very permeable coarse sand layer. Drill mud was removed with a methanol flamed spatula before samples were taken to minimize microbial contamination. This sampling regime was repeated again on Grenada Trip II.

### Lipid analysis

Sediment samples from bore holes were placed into sterile whirl-pack bags. These were held on ice after collection and stored frozen until processing. Lipids were extracted by the Bligh-Dyer procedure. Phospholipids were separated by silicic acid chromatography. The phospholipids were hydrolyzed, methylated and separated as the corresponding fatty acid methyl esters by capillary gas chromatography. Fatty acids were detected by flame ionization and identified by comparison to the elution time of known standards. These procedures have recently been published in detail (5).

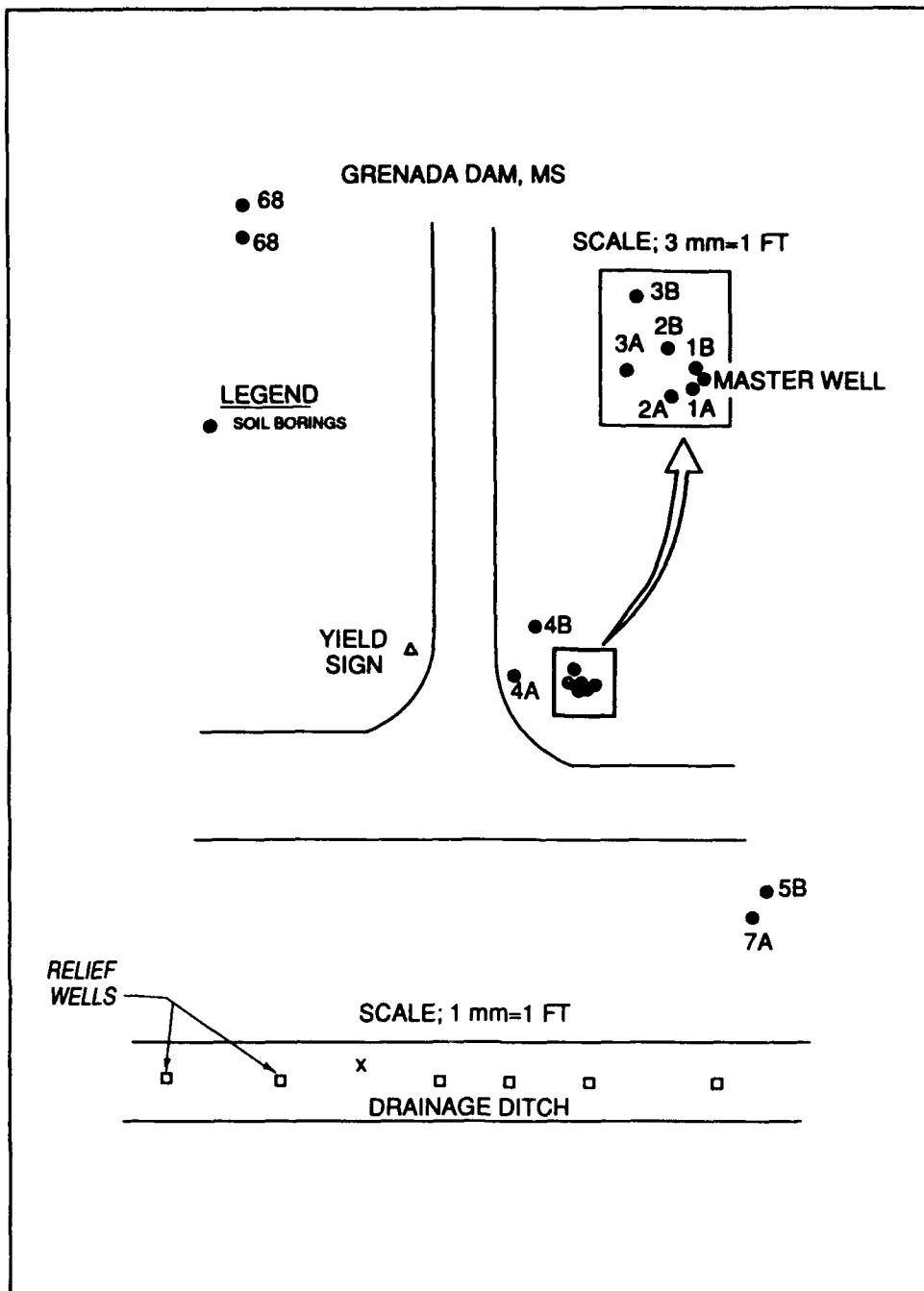


Figure C1. Grenada Dam, MS, sample borings before (B) and after (A) pumping the test well

## Autotrophic bacterial enrichments

Sediment subsamples were obtained aseptically from cores using a cut plastic syringe as a miniature coring tube. Sediment (0.5 ml) was transferred into Hungate tubes containing autotrophic media. Transfers into fresh media were made every 3 to 4 weeks. Table C1 describes the energy compounds/media types used and the chemoautotrophic and heterotrophic bacteria cultured with the corresponding media.

**Table C1**  
**Media Types Used in Sediment Enrichment Cultures**

Energy Compounds/Media Types	Cultured Bacteria
Winogradsky's	Iron precipitating heterotrophs
Acetate/ferric oxyhydroxide	Iron reducing heterotrophs
FeS	Iron and sulfur chemoautotrophs
Fe (HCO <sub>3</sub> ) <sub>2</sub>	Iron chemoautotrophs
Fe <sup>0</sup>	Iron chemoautotrophs
S <sup>0</sup>	Sulfur chemoautotrophs
S <sub>2</sub> O <sub>3</sub> <sup>-2</sup>	Sulfur chemoautotrophs
TsPepYe	Oligotrophic aerobic heterotrophs

### Iron precipitating bacteria

Iron precipitating heterotrophic bacteria were isolated from a modified Winogradsky's medium. This medium consisted of ferric ammonium citrate 3 g/L, Difco agar 12 g/L, plus a modified Hutner's mineral base (6). Sediment was streaked directly onto the agar plates from Grenada Trip 1. These plates were incubated at room temperature for 2 weeks. Isolated colonies were picked and streaked onto a trypticase soy medium to determine if non-iron precipitating heterotrophic contaminants were present which were not capable of utilizing citrate as a carbon-energy source. Colonies from this medium were streaked back on the modified Winogradsky's to confirm iron precipitation.

### Iron reducing bacteria

Iron reducing heterotrophic bacteria were enriched from sediments in a liquid medium consisting of mineral salts media supplemented with 40 mM acetate and 40 mM Fe(III) oxyhydroxide (7).

### **Heterotrophic colony forming units (CFU)**

At the time of collection, sediment was blended (Waring blender, 5 min) in 0.02-percent phosphate buffer pH 6.8, serially diluted and spread plated onto the standard mineral salts solution amended with trypticase soy (200 mg/l), yeast extract (5 mg/l) and Difco agar (12 g/l). Plates were incubated at room temperature for 3 weeks at the ambient temperature of 25° C before the CFU were counted.

### **Fluorescent microscopy**

Acridine orange (1 mg/ml) was used as a nucleotide stain as described by Porter and Feig (8). Relief well water samples were filtered onto 0.2  $\mu$ m Nuclepore filters which were counterstained with Irgalan black. A Zeiss standard epifluorescent microscope was fitted with an Olympus OM1 for the photomicrographs illustrated.

### **Scanning electron microscopy and X-ray diffraction analysis**

Water samples from pressure relief wells were filtered onto 0.2  $\mu$ m Nucleopore filters, fixed 20 min in glutaraldehyde (2 percent) and dehydrated in an acetone series. Specimens were mounted onto studs, critical point dried and gold coated. The X-ray diffraction analyses were performed by Dick Williams and John Dunlap of the University of Tennessee Biology Department.

## **Results**

### **Water chemistry**

The water chemistry of the pumped well is depicted in Table C2. There is a high iron content (>10 mg/l) in this well. These analyses were performed under the direction of the Army Corps of Engineers Waterways Experiment Station (WES).

### **Autotrophic enrichments**

A variety of morphological types have been selected. Fifth generation transfers have been made from the first trip. These enrichments demonstrate the loss of diversity desired in multiple transferred cultures. Many cultures contain only one or two morphological types as exhibited in Figures C2 and C3. Several additional tests are necessary to confirm autography. Many different morphological forms (i.e. rods, filaments) indicate the diversity of bacteria in the sediments below the dam. They were wide-spread in their vertical and horizontal distribution.

**Table C2**  
**Water Chemistry Data for Grenada Dam Pumped Well**

Chemical Constituents	Before Flow mg/l	After Flow mg/l
Silicon	6.3	6.8
Iron	11.9	12.2
Manganese	0.9	0.8
Calcium	16.4	17.2
Magnesium	6.8	8.0
Phosphate	<0.15	<0.15
Nitrate	<0.20	<0.20
Chloride	6.9	6.3
Alkalinity (CaCO <sub>3</sub> )	91.2	86.8
Hardness (CaCO <sub>3</sub> )	69.2	75.9
Total dissolved solids	130.0	137.0
Total solids	288.0	290.0
Note: Specific conductance		umho/cm
221		218



Figure C2. Epifluorescent micrograph (100x). Acridine orange strain. Fe<sup>0</sup> enrichment culture of sediment



Figure C3. Epifluorescent micrograph (100x). Acridine orange stain.  
 $\text{Fe}(\text{HCO}_3)_2$  enrichment culture of sediment

### Iron precipitating bacteria

Seventeen isolates precipitated iron initially when grown on the modified Winogradsky's medium. Table C3 documents some characteristics of these isolates. These "iron bacteria" are diverse as demonstrated by the Gram stain, motility, cell and colony morphology. Two of these bacterial strains (1g5clfc, 1g7clfc) have lost the ability to precipitate iron from ferric citrate. Six of these isolates cannot precipitate ferric iron without citrate. One organism (1g6g1fc) can precipitate  $\text{Mn}^{++}$ . Several of these organisms form copious slime which indicates their potential in fouling consortia.

### Iron reducing bacteria

Many bacteria are capable of reducing iron heterotrophically when  $\text{O}_2$  becomes limiting. The solubilization of iron was detected as the iron became reduced in enrichment cultures inoculated with sediment sampled at a 20 ft depth from all the borings. The approximate number of iron reducing bacteria was between 1 and 100/gdw by the most probable number (MPN) technique. There was no reduction of iron from cultures inoculated with sediments at depths greater than 20 ft.

**Table C3**  
**Characterization of "Winogradsky's Positive" Bacterial Isolates from Grenada Dam Sediments**

ID #	Colony Description TST/FcCit	Gram RXN	Cell Morphology Plate/Broth Dimensions (um)
Ig1a1c	4mm, circular, entire, yellow white, opaque metallic sheen, umberonate, depressed center	+	1x2-3, ovoid
Ig3d1c	1-2mm, circular, entire, yellow, opaque <1mm, dark center, irregular, rugose	-	0.5-1x2-3, granules
Ig4a1c	4-5mm, circular, flat, entire, viscous, brown <2mm, metallic sheen	-	0.5x2-4
Ig5c1c	translucent, irregular spreading margin concentric, metallic sheen, rugose	-	0.7x0.7-2
Ig5a1c	3-4 mm, circular, entire, convex, yellow, opaque metallic sheen	+	0.5x2
Ig5e2c	3-4mm, circular, entire, convex, yellow white, opaque metallic sheen	+	1x2-3
Ig6b1c	2-3mm, circular, entire, clear, translucent poorly defined margin, very viscous	-	0.7x3
Ig6d1c	1mm, circular, entire, translucent dark center	+	0.5x1-2
Ig6d2c	3-4mm, circular, entire, flat, white, opaque metallic sheen, depressed center	-	0.7x1-4
Ig6g1c	rugose, dry, opaque, flesh-colored filamentous margin, metallic sheen, rugose	-	0.5x2-3 some filaments
Ig6g2c	2-3mm, circular, entire, yellow, translucent very viscous, metallic sheen	-	1x4
Ig7c1c	4-5mm, ovoid, pulvinate, white, translucent metallic sheen, dark center	+	0.7x2-4
Ig7c2c	2-3mm, circular, entire, concave, yellow dark center, metallic sheen	-	short rods long thin pleomorphic
Ig7e2c	2-3mm, thin spreading margin translucent	-	0.7x1

(Sheet 1 of 3)

Table Abbreviations: ND = Not Determined; RXN = Reaction; MAL = Malate; SUC = Sucrose; IND = Indole; MOT = Motility; CAT = Catalase; OXID = Oxidase; RED = Reduced; FcCit = Feric Citrate; XYL = Xylose; ARG = Arginine; LYS = Lysine; ORN = Ornithine; Star = Starch; 0+ = Aerobic; 0- = Anaerobic; PHEN ALA = Phenyl Alanine; TSY = Trypticase Soy + Yeast Extract

**Table C3 (Continued)**

ID #	MOT	CAT	OXID	Metals Precipitated From			Dextrose			XYL			ARG		
				FeCit	FE++	Mn++	Fe+++	NO <sup>3</sup>	RED	O+	6	MAL	SOC	XYL	ND
lg1a1fc	-	+	-	+	+	-	-	-	-	-	-	-	-	-	-
lg3d1fc	+	+	+	+	+	-	-	+	+	+	+	-	-	-	-
lg4a1fc	+	+	ND	ND	+	+	-	-	-	-	-	-	-	-	-
lg5a1fc	-	-	-	+	+	+	-	-	-	-	-	-	-	-	-
lg5e2fc	-	-	-	+	+	+	-	-	-	-	-	-	-	-	-
lg5e21c	-	-	-	+	+	+	-	-	-	-	-	-	-	-	-
lg5b1fc	-	-	-	+	+	+	-	-	-	-	-	-	-	-	-
lg6d1fc	-	-	-	+	+	+	-	-	-	-	-	-	-	-	-
lg6d2fc	-	-	-	+	+	+	-	-	-	-	-	-	-	-	-
lg6g1fc	-	-	-	+	+	+	-	-	-	-	-	-	-	-	-
lg6g2fc	-	-	-	+	+	+	-	-	-	-	-	-	-	-	-
lg7c1fc	-	-	-	ND	ND	ND	-	-	-	-	-	-	-	-	-
lg7c2fc	-	-	-	ND	ND	ND	-	-	-	-	-	-	-	-	-
lg7e2fc	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

(Sheet 2 of 3)

- Note: See page C10 for table abbreviations.

**Table C3 (Concluded)**

ID #	LYS	ORN	UREA	ONPG	IND	STAR	PHEN ALA	CIT	Preliminary Identification
Ig1afc	-	-	-	-	-	-	-	+	Coryneform
Ig3d1fc	-	-	-	-	-	-	-	-	Vibrio
Ig4a1fc	-	-	-	-	-	-	-	-	Pseudomonas
Ig5c1fc	-	-	-	-	-	-	-	-	Pseudomonas
Ig5e2fc	-	-	-	-	-	-	-	-	Coryneform
Ig6b1fc	-	-	-	-	-	-	-	-	Coryneform
Ig6d1fc	-	-	-	-	-	-	-	-	Acinetobacter
Ig6d2fc	-	-	-	-	-	-	-	-	Coryneform
Ig6g1fc	-	-	-	-	-	-	-	-	Acinetobacter
Ig6g2fc	-	-	-	-	-	-	-	-	Aeromonas
Ig7c1fc	-	-	-	-	-	-	-	-	Pseudomonas
Ig7c2fc	-	-	-	-	-	-	-	-	Coryneform
Ig7c21c	-	-	-	-	-	-	-	-	Acinetobacter
Ig7e2fc	-	-	-	-	-	-	-	-	Moraxella

(Sheet 3 of 3)

- Note: See page C10 for table abbreviations

## Heterotrophic CFU

Figure C4 documents the number of heterotrophic microbes and their densities in relation to the pumped well. There were greater numbers of CFU in borings 2 and 6. Bacteria tended to concentrate in the shallow sediments at depths of 20 ft. Again there were a variety of these organisms as depicted by their Gram reactions, morphologies, and pigmentation (data not shown). Many of these organisms produced slime on the CFU media. The solum bentonite drilling mud which was also sampled contained  $<10^1$  bacteria/gdw, as determined by spread plating onto the heterotrophic medium. These organisms

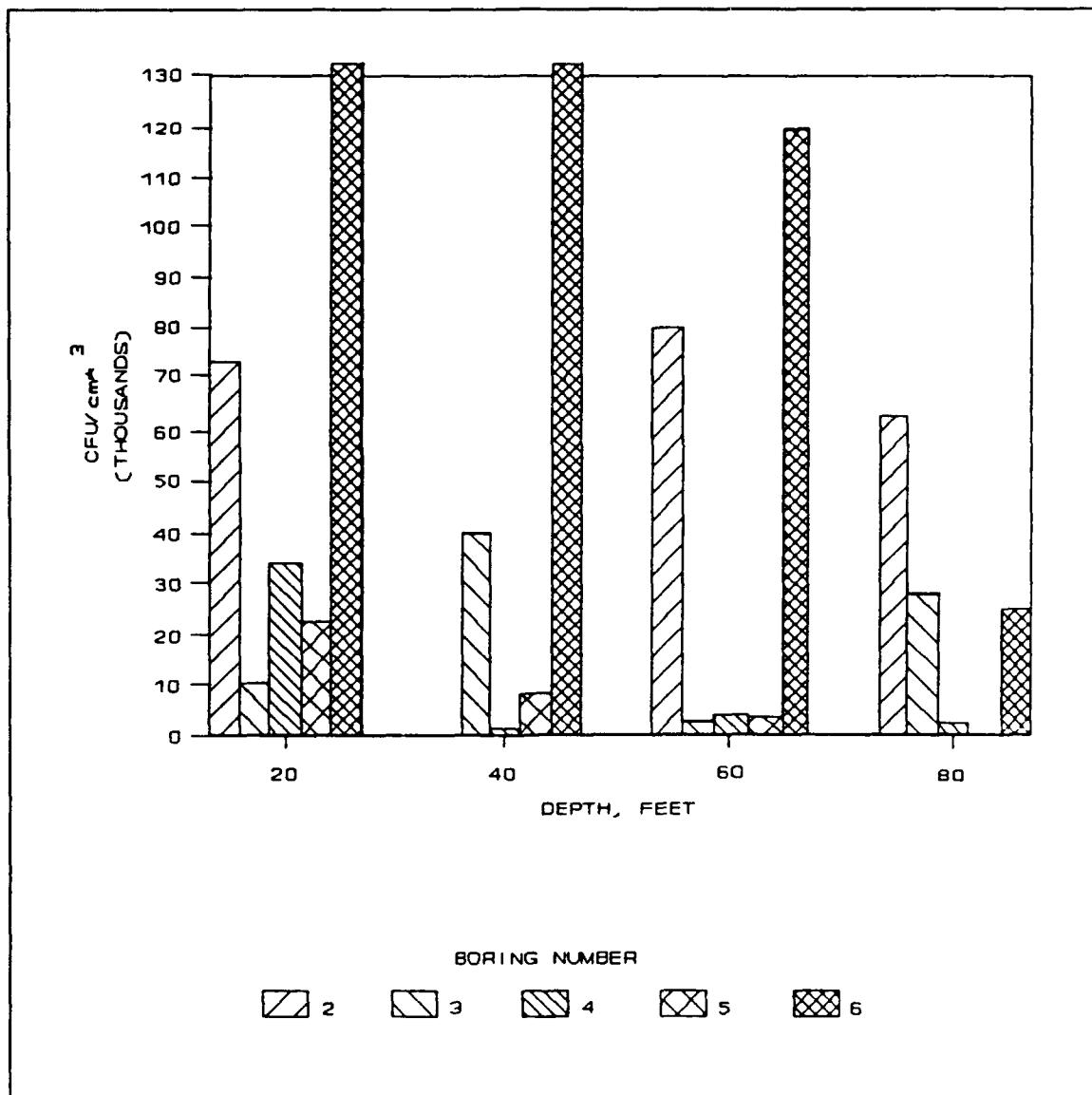


Figure C4. Plate count data (CFU) on heterotrophic medium from borings 2a - 6a, after pumping

were predominately *Bacillus* sp. No organisms ( $<10^1$  bacteria/gdw) were detected by the same technique in the chlorinated drilling mud. This evidence supports that these CFU represent indigenous culturable organism. Twenty-seven isolates were selected and purified from Trip I for later characterization.

### **Lipid characterization**

Results from the phospholipid fatty acid (PLFA) analysis for Trips I and II (before and after pumping) are illustrated in the following section. Figure C5 summarizes the microbial biomass (total PLFA, pM/gdw) found in sediments with respect to depth and distance (boring No.) from the pumped well before and after pumping. Microbial biomass is concentrated in the upper 20 feet. The total quantity of biomass across the sampled area was not greatly affected by this period of pumping.

The relative bacterial contribution to sediment biomass ( $\text{a}15:0 + \text{a}15:0/16:0$ ) before and after pumping in the sediment core at 3 ft from the well is depicted in Figure C6. The proportion of bacterial biomass increased after pumping at the sample boring closest to the pumped well (3 ft). The peak bacterial biomass, after pumping, was at a depth of 40 ft in this boring.

The eucaryotic contribution to sediment biomass (polyenoics/16:0) before and after pumping is illustrated in Figure C7. The proportion of eucaryotes increased accordingly with depth after pumping. Borings 5 and 6, farthest from the pumped well, were the exception. The greatest increase in eucaryotic biomass was in the bored samples at 80 and 27 feet from the pumped well. This is illustrated in Figure C8.

Figure C9 demonstrates lipids associated with *Desulfobacter* (10Me16:0) and *Thiobacillus* (Cy17:0). *Desulfobacter* is an anaerobic sulfate reducing anaerobic bacterium and *Thiobacillus* is a sulfur oxidizing bacterium.

### **Relief well microbiology**

Prussian blue and acridine orange stains of bacteria from relief wells No. 2 and No. 92 (dam relief well system) are depicted in Figures C10 and C11, respectively. Scanning electron micrographs of these same wells are illustrated in Figures C12, C13, and C14. Relief well No. 2 seems to exhibit greater microbial diversity than No. 92, including a variety of filamentous bacteria and even diatoms (note frustules in Figure C13). X-ray diffraction elemental analysis of a *Leptothrix* filament is represented in Figure C15. This documents the iron content associated with *Leptothrix* sheaths.

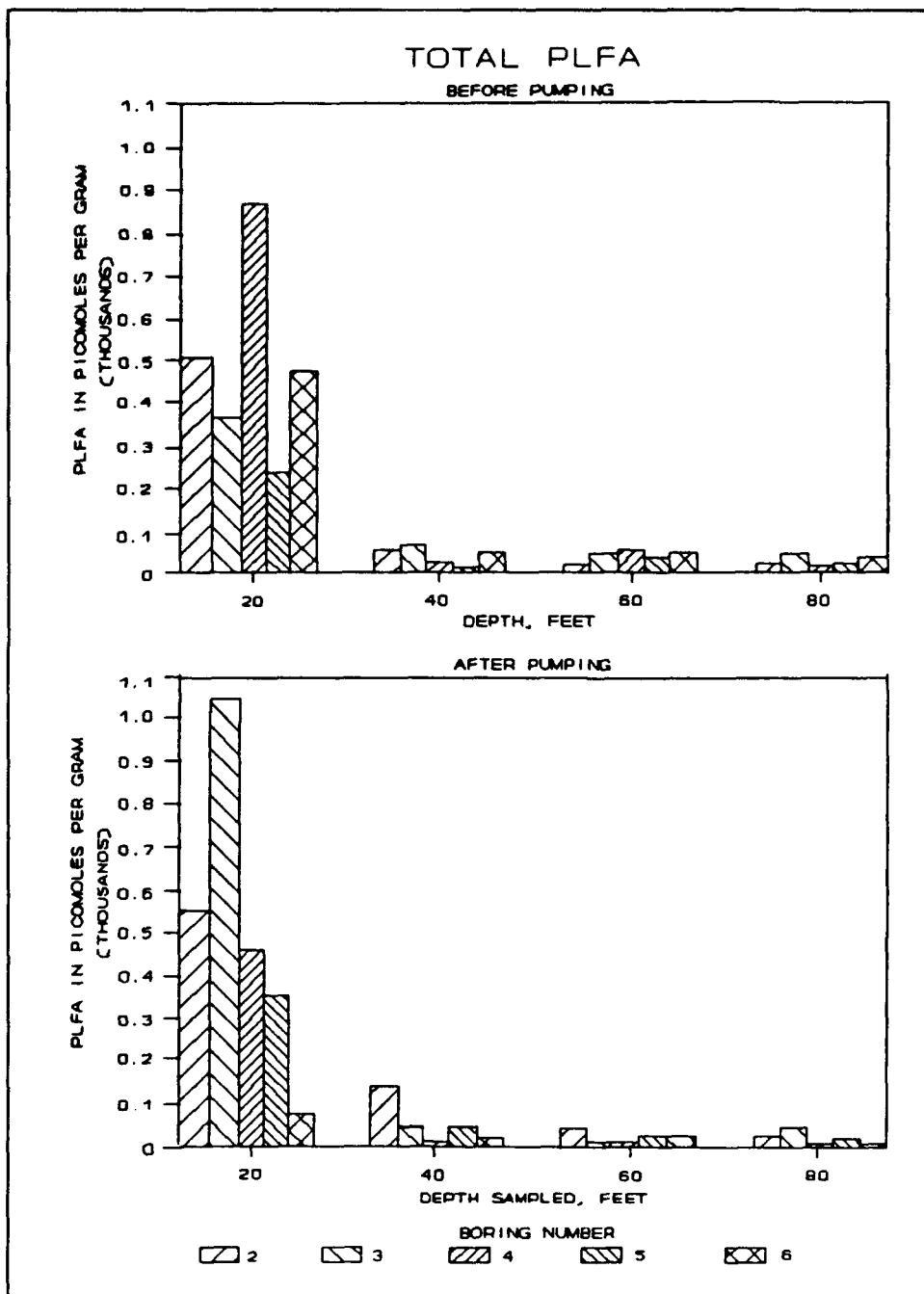


Figure C5. Microbial biomass (total phospholipid fatty acids) in sediments versus depth and distance from pumped well

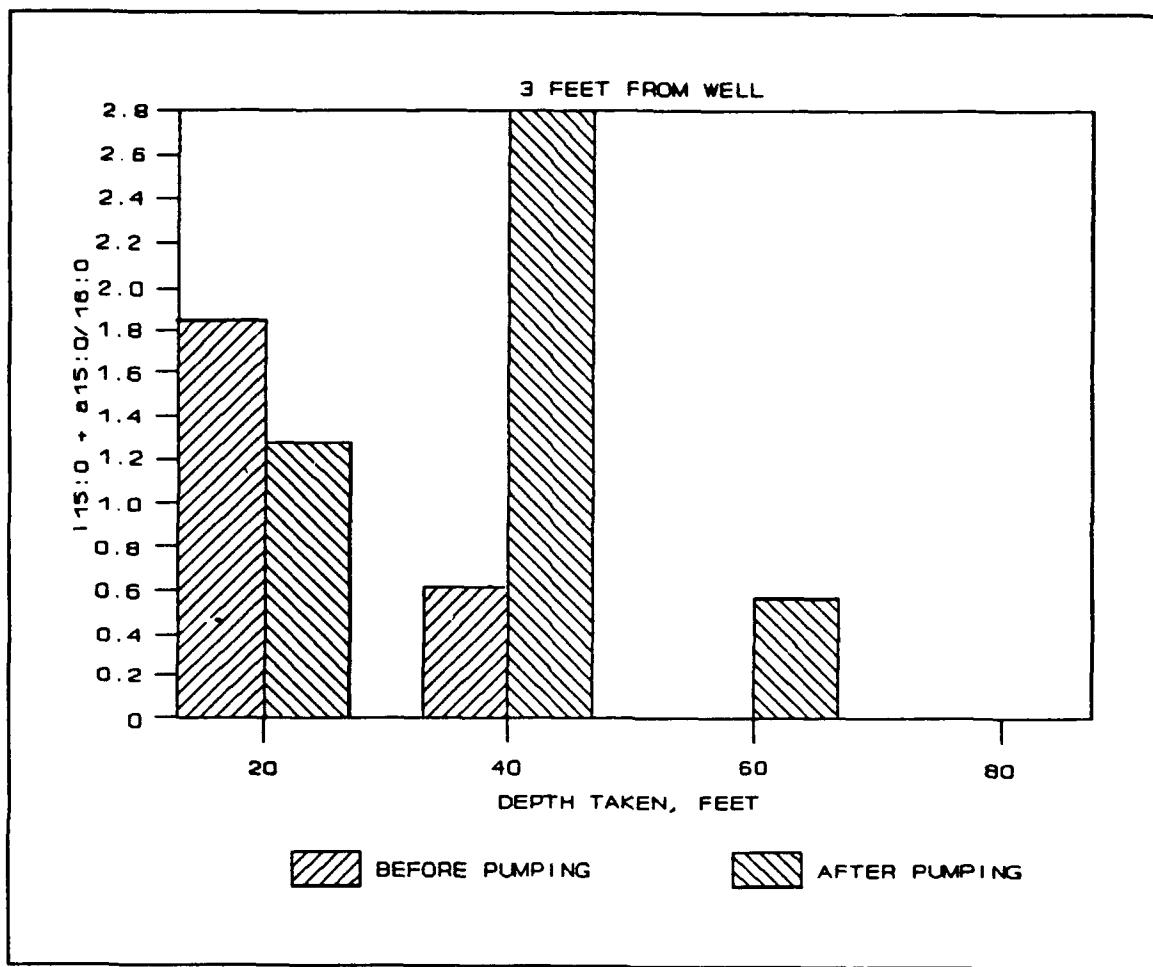


Figure C6. Bacterial contribution to sediment biomass ( $i15:0 + a15:0/16:0$ ) in sediment 3 ft from the well

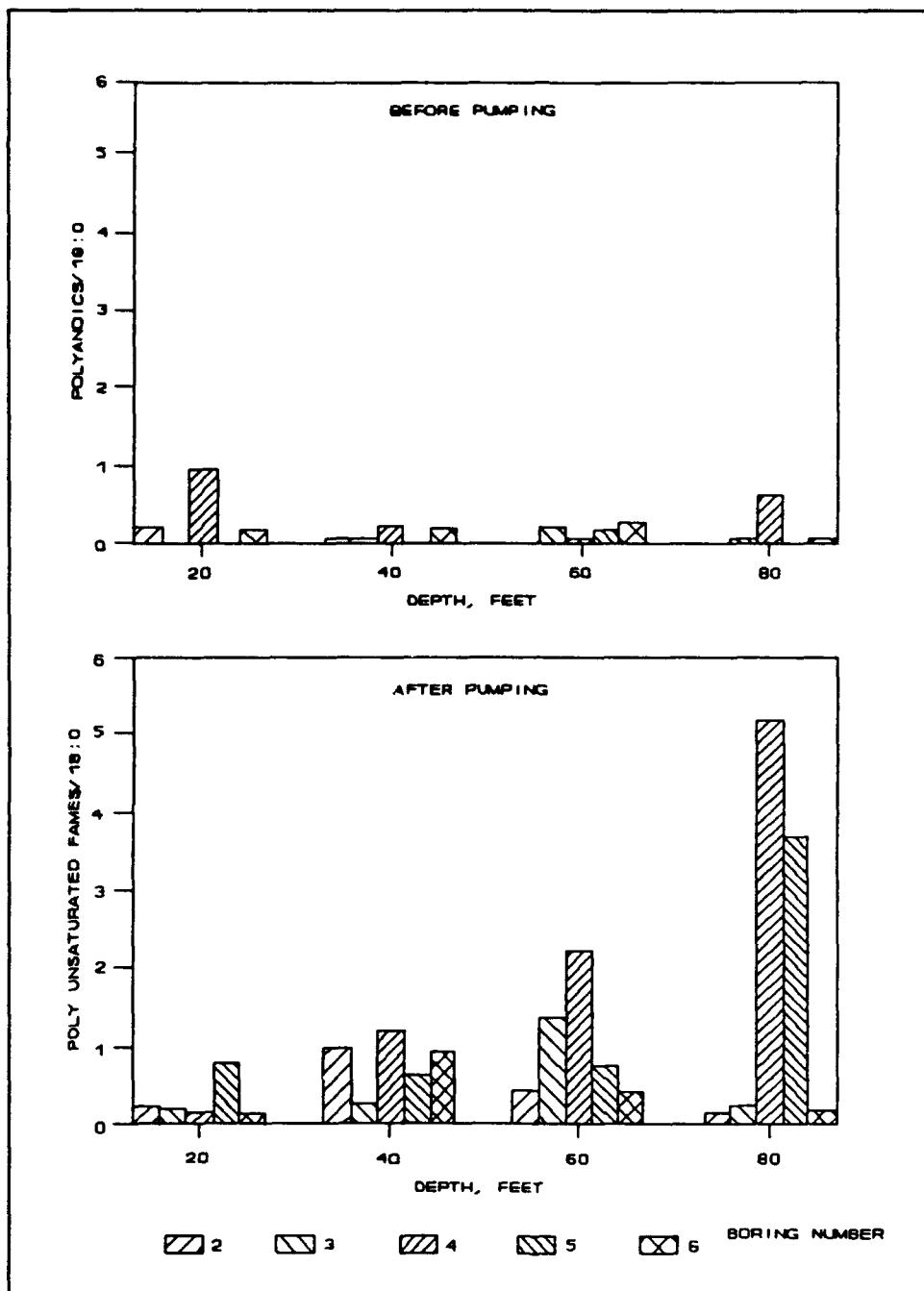


Figure C7. Eucaryotic contribution to sediment biomass (polyenoics/16:0)

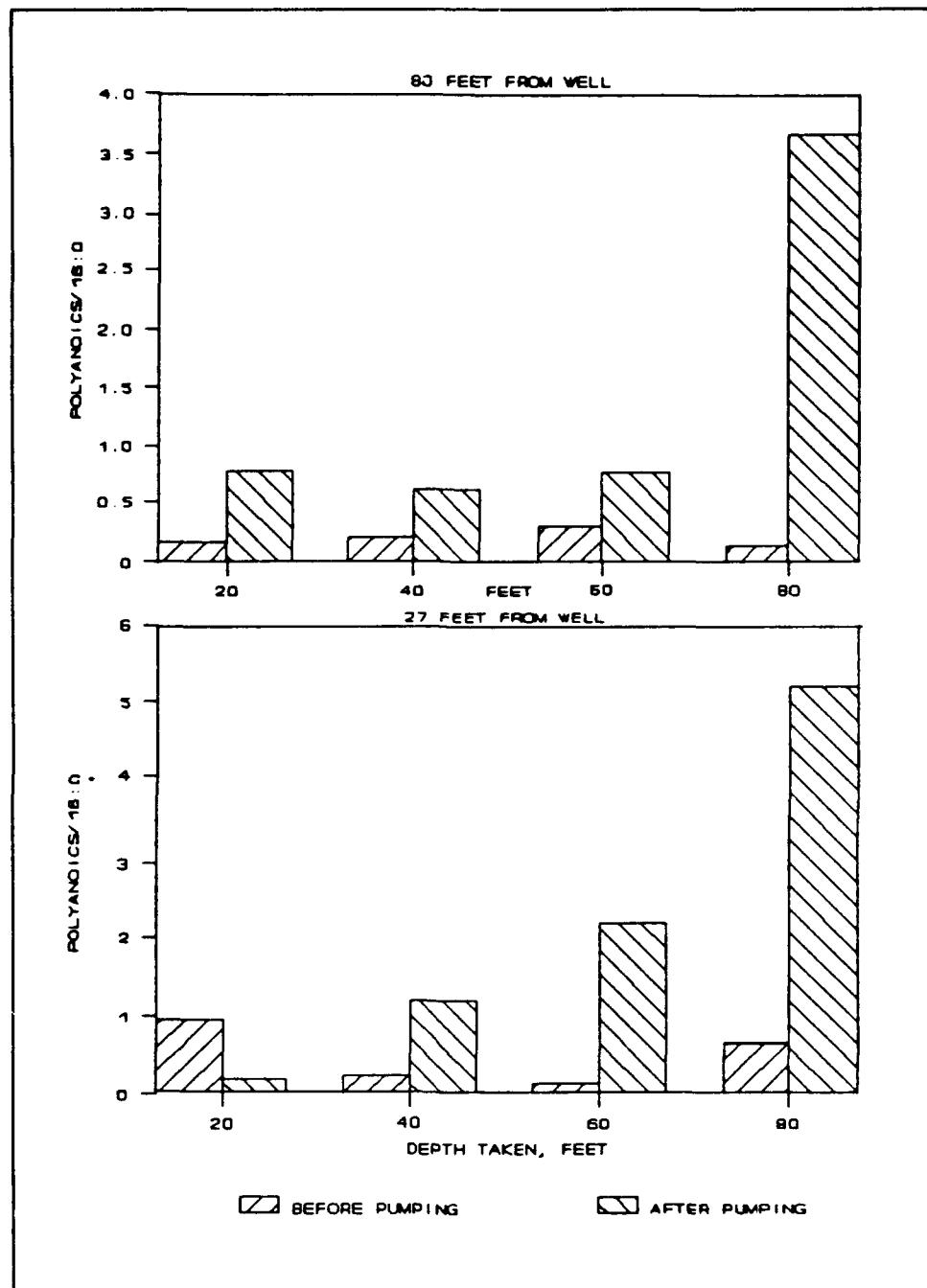


Figure C8. Eucaryotic contribution to sediment biomass at 27 and 80 ft from pumped well

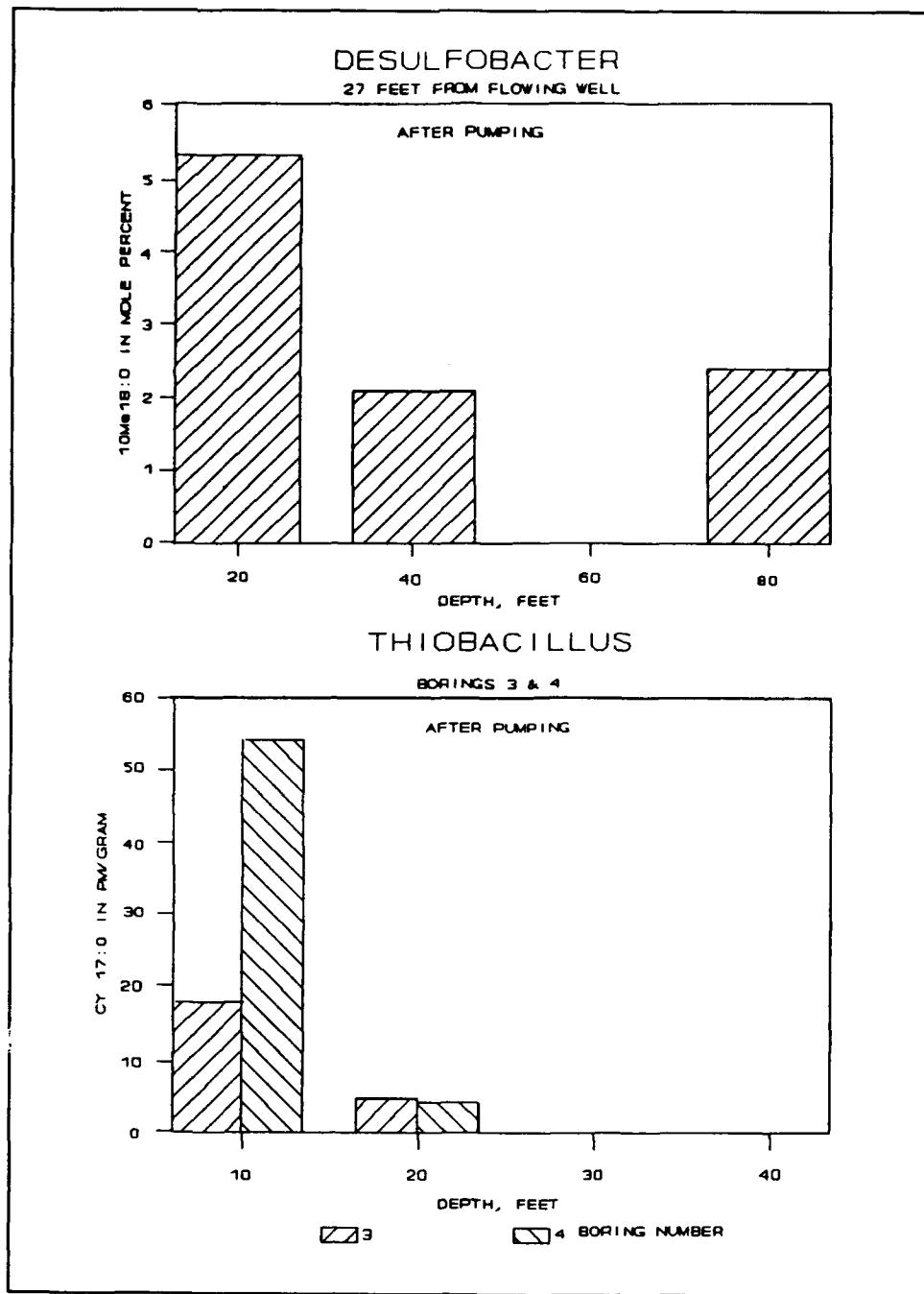


Figure C9. Lipids associated with Desulfovobacter (10Me16:0, mole %) and Thiobacillus (Cy17:0, pm/gram-dry weight)

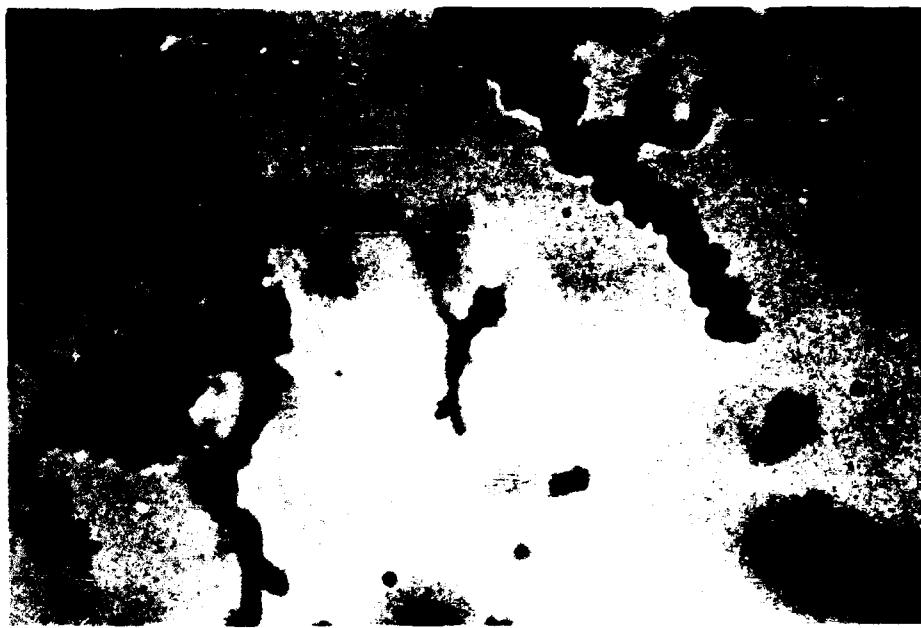


Figure C10. Light micrograph (100x). Relief Well No. 2. Prussian blue stain



Figure C11. Epifluorescent light micrograph (100x). Relief Well No. 92. Acridine orange stain

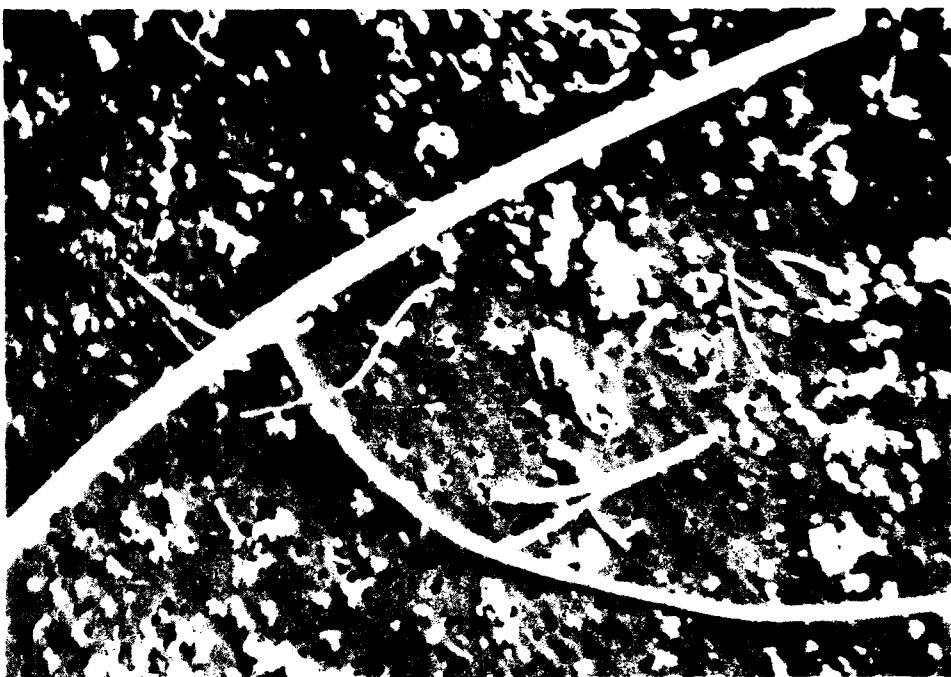


Figure C12. Scanning electron micrograph, Relief Well No. 2

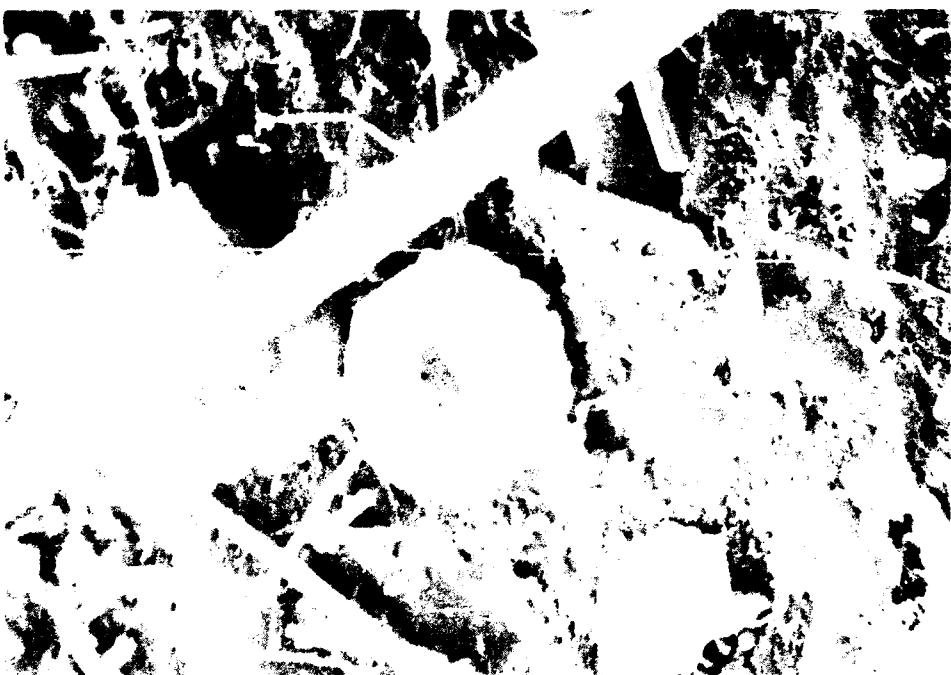


Figure C13. Another view with scanning electron micrograph, Relief Well No. 2

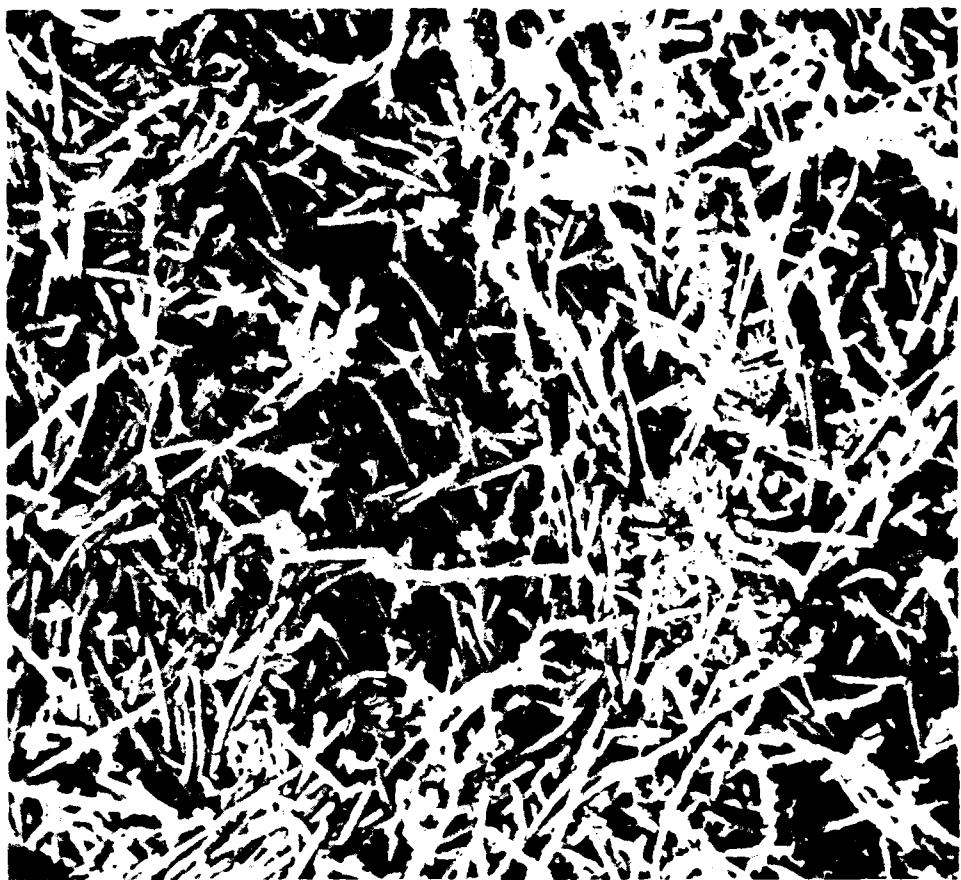


Figure C14. Scanning electron micrograph, Relief Well No. 92

EG&G Ortec System 5000  
Spectrum Plotting Program  
Printplot V02.05

Sample ID: Fe bacterium AM001  
Energy Range: 0-10 keV 10 eV/ch  
Preset: Off  
Real Time: 263.25 sec. Live Time: 230.08 sec.  
17% Deadtime 7173 Counts/Second  
Acquisition date: 26-Sept-85 Acquisition time: 10:08:47  
Cfs 2K

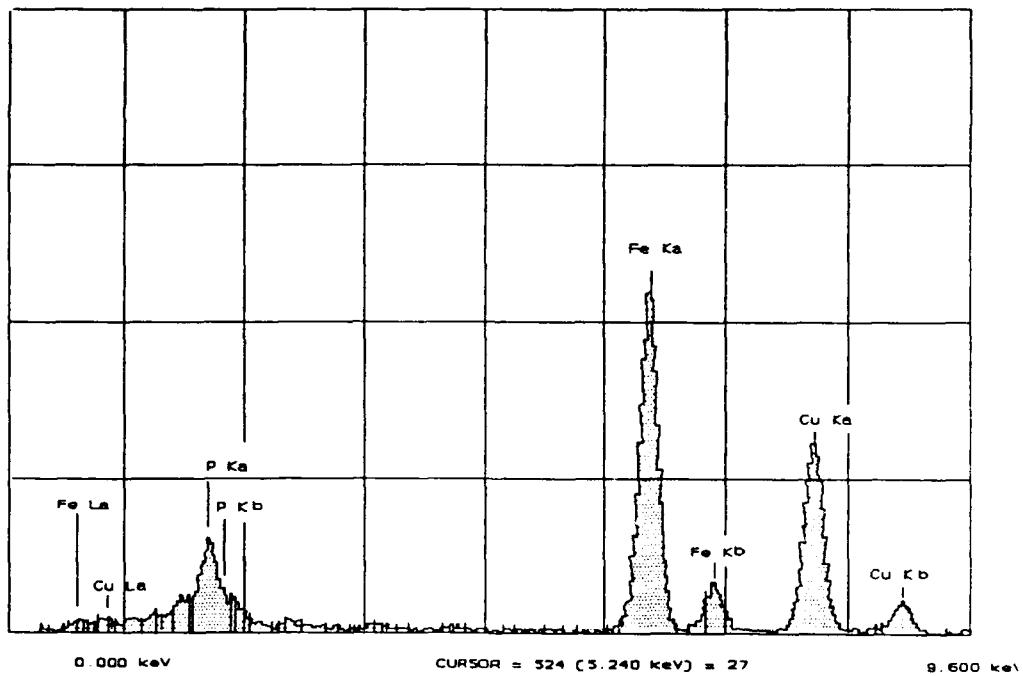


Figure C15. X-ray diffraction elemental analysis of Leptothrix filament from Relief Well No. 92

EG&G Ortec System 5000  
Spectrum Plotting Program  
Printplot V02.05

Sample ID: Fe bacterium AM001  
Energy Range: 0-10 keV 10 eV/ch  
Preset: Off  
Real Time: 263.25 sec. Live Time: 230.08 sec.  
17% Deadtime 7173 Counts/Second  
Acquisition date: 26-Sept-85 Acquisition time: 10:08:47  
Cfs 2K

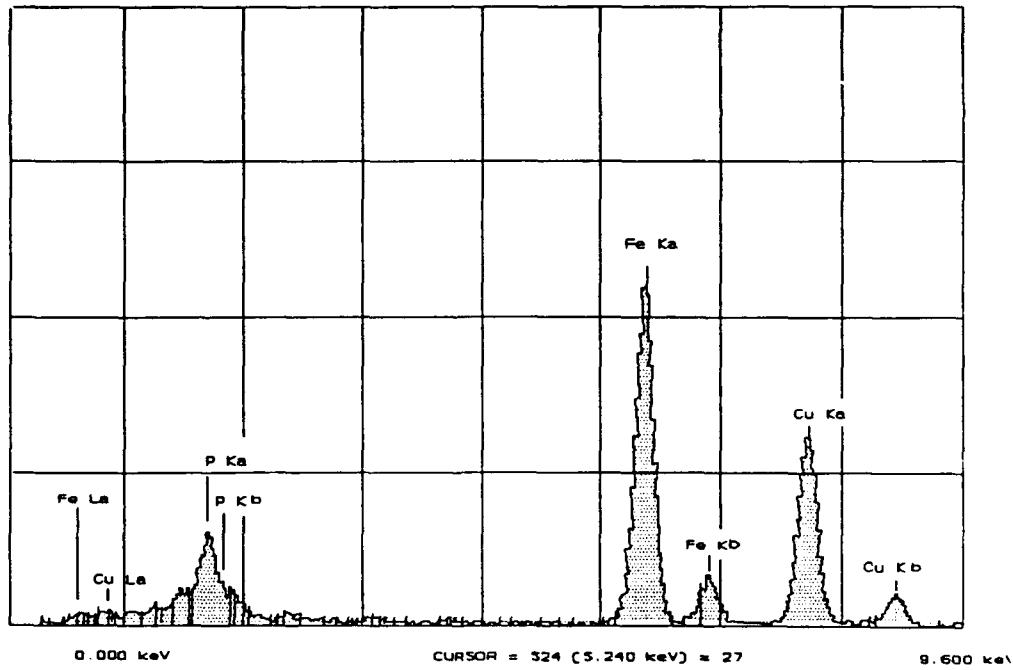


Figure C15. X-ray diffraction elemental analysis of Leptothrix filament from Relief Well No. 92

## Discussion

The variety of "iron bacteria" in the sediment below the dam depicts a complete iron cycle; iron oxidizers, reducers and precipitating bacteria. Additionally, sulfur oxidizers and reducers may be present in the sediment as indicated by the presence of lipids associated with these organisms. Sulfur oxidizers have also been successfully cultured. Isolation of the anaerobic sulfate reducers was not attempted. Lipids were found which indicate the presence of *Desulfovobacter*, a sulfate reducer. The higher concentrations of *Desulfovobacter* fatty acids associated with shallower depths are probably due to the higher organic content of the soils as these organisms are heterotrophs. Sulfate reducing bacteria can contribute to biofouling and corrosion (2, 9).

Several of the filamentous organisms seen in the relief wells by microscopy and in enrichment cultures remain unidentified. *Gallionella* was identified and is a proven chemoautotroph. Other chemoautotrophs such as *Thiobacillus* are not morphologically distinct but may be equally important in determining the type of fouling at Grenada Dam. To determine if the ferrous iron can support an autotrophic community, further dilutions of these autotrophic cultures are being conducted. Each subsequent dilution removes organic carbon that obscures results. The concept of mixotrophy resolves that organisms, such as *Sphaerotilus* and *Leptothrix*, are capable of oxidizing organic and inorganic constituents. This may or may not be coupled to energy yielding reactions.

The predominance of autotrophy to heterotrophy as an energy source for microbial productivity is relevant to the fouling problem. The concentration of iron in the water analysis of the pumped well suggests that there is sufficient reduced iron to support chemoautotrophic bacteria. However, there is much less energy available from oxidation of inorganic compounds than from organic substrates. Additionally, many of these organisms fix carbon dioxide which suppresses growth efficiency. Energy obtained from chemoautotrophic reactions may limit fouling quantities of growth to high water velocity areas. The diffusion of oxygen is also imperative for these reactions to occur. Heterotrophs, dependant on organic carbon excreted, would grow in conjunction with these organisms. This environment would occur in proximity to the well so that the fouling would be restricted to that immediate area. In some relief wells horizontal flow may exceed vertical flow, so that "non-flowing" relief wells may be fouled by the same mechanism. Treatment and cleaning of these wells might be effective on a relatively small area. The bad news is there is a tremendous potential for regrowth or seeding of these organisms at the Grenada Dam site. Distance of biocide penetration would control the time required for regrowth.

A complete water chemistry analysis including concentrations of ferrous, ferric iron, sulfide, sulfur, sulfate and dissolved organic carbon, is needed from several relief wells and the pumped well. This would allow further elucidation as to the energy mechanisms available to the microbial communities at these sites.

Reduced forms of iron and sulfur may be produced by heterotrophic consumption of organic material in the oxygen limited sediments in the lake bed behind the dam. This would impact the communities associated with relief wells at this site and others.

There are high numbers of heterotrophic bacteria in the sediments surrounding the dam. The higher proportion of culturable bacteria CFU:PLFA at boring 6 could illustrate the input of organic carbon from the adjacent spillway. As the sediment in this area would be more eutrophic, a higher proportion of these organisms would be able to produce CFU.

A very taxonomically diverse group of heterotrophic bacteria were found to precipitate iron. These "iron precipitating bacteria" were ubiquitous in these sediments.

Data from Trips I and II suggest that flow increased the relative bacterial population in the boring closest to the pumped well. This biomass was maximum at the 40 ft depth. This could be due to increased vertical flow. The CFU data from boring 2 after pumping also indicates a higher bacterial biomass relative to borings 3, 4, and 5. PLFA in boring 6 are at variance with CFU data. Boring 6 demonstrated among the lowest PLFA concentration and the highest CFU.

There was a high proportion of eucaryotic biomass in these samples from Grenada Dam. Eucaryotes, microorganisms with a membrane bound nucleus, include fungi, algae, and protozoa. Some fungi and molds were found in the sediment samples plated onto the heterotrophic medium. This medium is not designed for optimum growth of fungi and their numbers were not significant compared to bacterial CFU. Protozoa from aquifer sediments are currently being isolated and characterized by Bill Ghiorse (personal communication). They may be important predators of bacteria in sediments and some have suggested that they may be used to control bacterial biofouling.

The microscopic examination of two relief wells reveal entirely different microbial communities. Relief well No. 92 was predominately *Leptothrix* sp. A sample from relief well No. 2 was very diverse exhibiting several types of filamentous bacteria including *Gallionella* sp. This illustrates the potential for markedly different fouling types in the relief wells across the dam face. This may be due to

- a. *Velocity of flow.* This would be evident if a redox gradient is discovered across the dam face. PLFA patterns would demonstrate similarity by proximity.
- b. *Variable geology thus water chemistry.* As the old river meandered, deposits would be irregularly lain across the area which is now the dam foundation. There would be variability in the well water chemistry and resultant microbial communities and little correlation between well proximity.

c. *Sampling error.* This observation could be at fault due to sampling error. The material could have come from a different depth of the well and there may be a vertical gradient of organisms on the well screen. This possible sampling artifact will be studied by video camera review of the well in the Phase II study.

The general lack of viability of relief well bacteria, indicated by the nucleotide stain acridine orange, is evident in Figure C11. Very few of the bacteria illustrated by light and electron microscopy in Figures C10, C12, C13, and C14 may be alive. For treatment to be effective in these wells, the dead mineral encrusted filaments must be removed physically, or in some cases, filaments might wash out by natural water flow. It is evident that filamentous mineral encrusted bacteria will physically plug a well. We do not know the age or longevity of these filaments; after death, however, they may be resistant to natural degradation.

## Conclusions

Bacterial groups associated with biofouling are ubiquitous in the sediments surrounding Grenada Dam. Treatment regimes relying on initial kill plus cleaning and disregarding inhibition may not be effective due to rapid reseeding or reinoculation of the well area.

Iron is available in high concentrations and organisms have been identified and cultured; therefore, chemoautotrophy may be energetically important at the Grenada dam site. Energetics of these organisms suggests that they may be restricted to the immediate well area. Treatment penetration area may be less important than frequency (see conclusion 1).

Water flow into the well represents a fortuitous input of energy and potential electron acceptor, oxygen. Under these conditions all wells age toward a finite lifetime and the rate may be controlled only by an effective rehabilitation treatment.

Initial examination of relief well microbiota reveals diversity in the microbial community structure between wells. Treatment regimes may not exhibit equivalent effectiveness (i.e. % recovery) in all wells.

Relief well fouling material may be predominately dead microbial cells and precipitated minerals. Cleaning methods which cause dissolution of these plugs should be used.

## Acknowledgments

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# Appendix D

## Biochemical Reports

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### Alton Report One

Table D1 includes the chemical and microbiological data for the listed relief wells during the December sampling period. Samples were collected at 3 ft below the surface in all well. Certain wells were also sampled at 15-ft depth to determine stratification. These wells were stratified, and in general, the lower depth contained the highest numbers of bacteria. Where two sampling depths were obtained, values were averaged for the figures presented.

Table D1 illustrates that waters from these wells exhibited a pH range of 7.2 to 7.8. The oxidation reduction potential, or redox, ranged from -40 mV to +220. Values of < 60 mV border on anaerobic. Relief Wells 16, 18, 21, and 22 redox and pH values may indicate an environment where ferrous iron and its subsequent oxidation to ferric oxyhydroxide may be a potential problem. This oxidation may occur through spontaneous chemical oxidation, or by iron oxidizing bacteria. Sulfate reducing bacteria were also detected in these wells (see Figure D1). These bacteria are anaerobes. It is possible that these bacteria produce sufficient sulfide as a metabolic end product, such that soluble (free ferrous) iron will not occur. Ferrous sulfide is poorly soluble.

The highest numbers of bacteria were the fermenters and the facultative bacteria (see Figures D2 and D3). Both of these physiological types of bacteria may grow in the absence of oxygen. Fermenters produce organic acids which may affect corrosion. In contrast, few bacteria developed in the heterotrophic medium devised to provide maximal counts of total bacteria in oligotrophic (nutrient poor) groundwaters (Figure D4). This indicates high organic loading and a fouling potential in these wells (Relief Wells 29, 30, 34, 36, 44, 46, and 92). Fouling (lowered well productivity) under similar conditions has been demonstrated in Rocky Mountain National Arsenal, Denver, CO. Higher organic loading permits more biomass, as more energy is available for growth.

**Table D1**  
**Chemical and Microbiological Data for Relief Wells During December Sampling Period**

Well #	Depth Feet	pH	Redox Mv	Avg Heterotrope (#/ML)	Fermenters (#/ML)	Avg Fermenters (#/ML)	Facultative (#/ML)	Avg Facultative (#/ML)	Sulfate Reducers/ML
16	3	7.3	-40	1.4E+05	1.4E+05	3.8E+04	3.8E+04	7.0E+04	6.2E+01
18	3	7.4	20	>10,000	>10,000	3.8E+04	3.8E+04	>10,000	>10,000
21	3	7.8	4	1.4E+05	1.4E+05	>10,000	>10,000	1.4E+05	1.4E+05
22	3	7.7	-3	3.8E+04	3.8E+04	3.8E+04	3.8E+04	3.8E+04	4.8E+01
29	3	7.5	220	3.5E+05	5.7E+06	1.6E+05	3.8E+05	1.1E+05	ND
	15	7.5	204	1.1E+07		6.0E+05		2.1E+05	ND
30	3	7.2	159	2.5E+07	2.5E+07	8.0E+05	8.0E+05	3.5E+05	3.5E+05
34	3	7.3	51	8.0E+04	3.4E+05	8.0E+05	7.0E+05	8.0E+05	5.5E+08
	15	7.4	87	6.0E+05		6.0E+05		1.1E+09	ND
36	3	7.6	84	3.5E+04	3.2E+05	6.0E+05	7.0E+05	1.1E+05	1.9E+05
	15	7.6	120	6.0E+05		8.0E+05		2.7E+05	ND
44	3	7.6	47	1.1E+06	1.1E+06	2.0E+06	2.0E+06	1.1E+06	1.1E+06
46	3	7.6	82	4.0E+06	2.1E+06	3.5E+06	7.3E+05	1.1E+06	1.1E+06
	15	7.6	-11	1.1E+05		1.1E+06		1.1E+06	ND
92	3	7.5	219	2.0E+06	2.0E+06	2.0E+06	6.0E+05	6.0E+05	ND

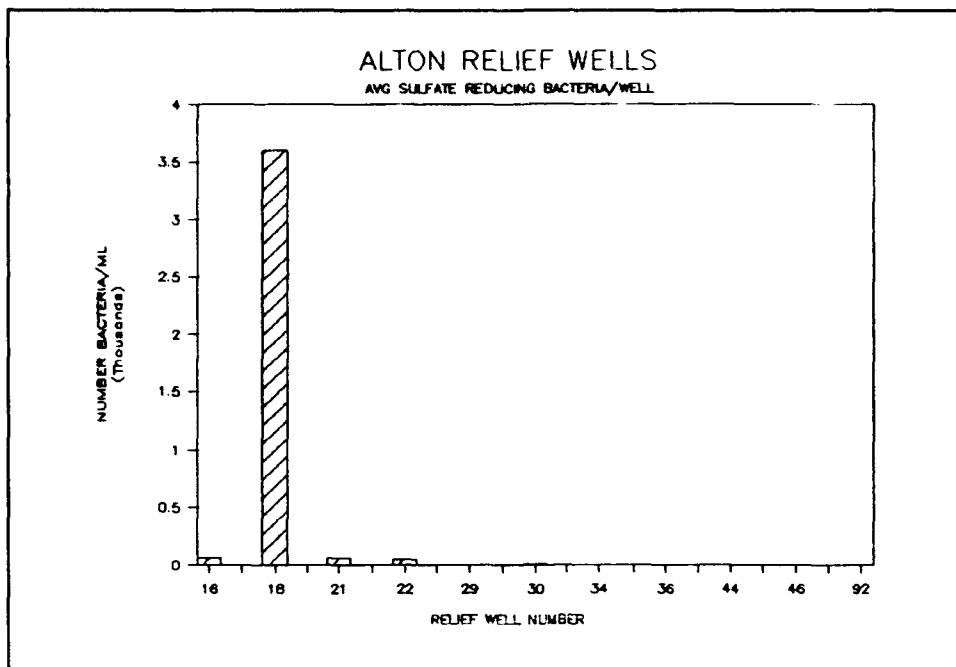


Figure D1. Sulfate-reducing bacteria per well

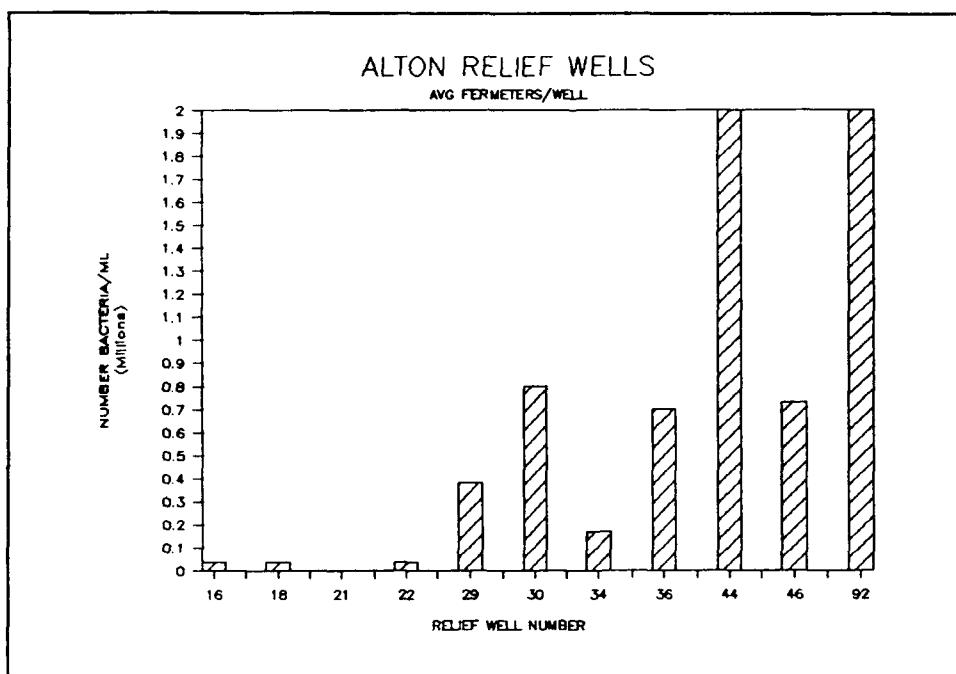


Figure D2. Fermenter bacteria per well

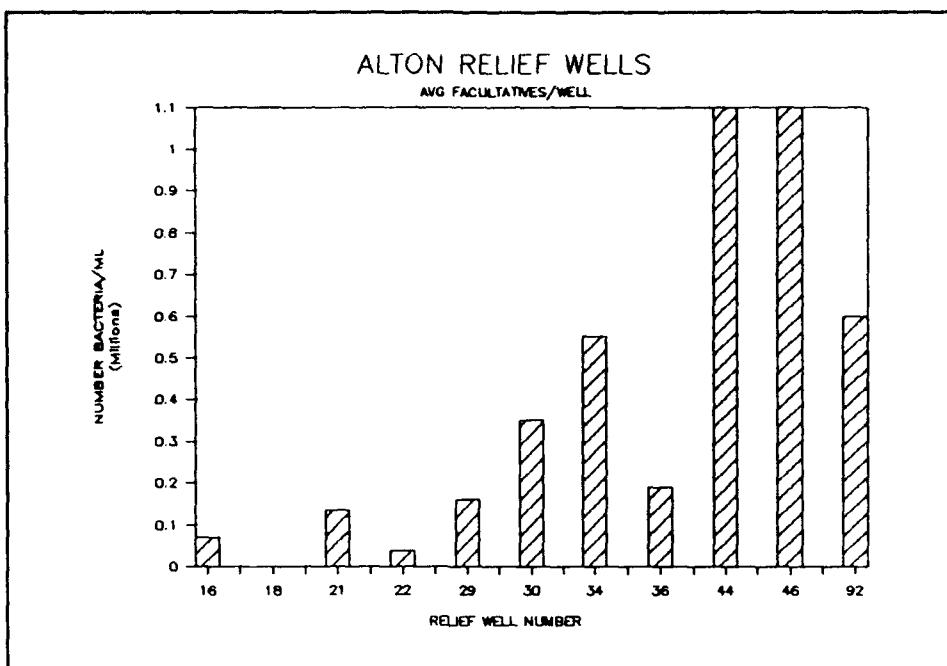


Figure D3. Facultative bacteria per well

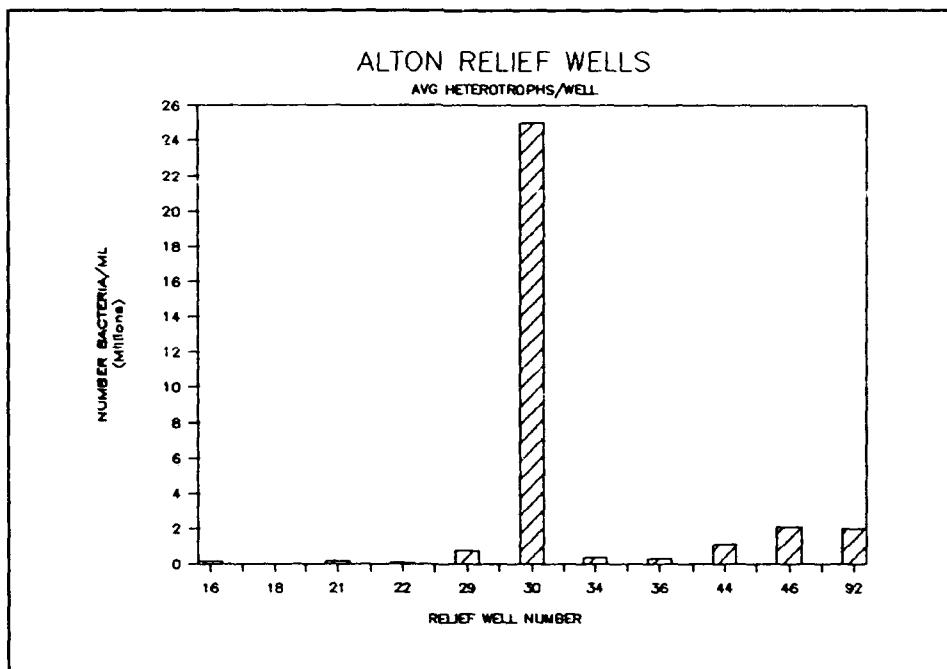


Figure D4. Heterotrophs per well

In summary, high organic loading of Relief Wells 29-92 may result in chronic biofouling, as has been the case in a similar environment. Wells 16-22 could present another type of microbial fouling if iron oxidizing bacteria are present in these wells. This could change seasonally and might be flow dependent as sulfide concentrations change in these well waters. We have seen more significant iron oxidizing bacterial problems at lower pH's (6.6-6.8) in Grenada, MS, and Long Branch, MO.

## A Report on the Microbiology of Relief Wells at Alton, IL<sup>1</sup>

On October 1 six Relief Wells (RW) at Alton, IL were evaluated for certain physiological types and population densities according to techniques and methods previously reported. Well waters were sampled using a Niskin bottle at top and bottom of the water column (top = 3 ft below water surface, bottom = 3 ft from well bottom). This approach was used to determine the presence and types of bacteria that may be stratified within the well where one sample will not suffice. The exception being RW22 which was sampled at three depths. The data for these wells is summarized in Table D2. None of the wells were flowing on this sampling date.

**Table D2**  
**Data Summary; Alton IL, Oct. 1989**

Well/Depth	ORP (mV)	Number Organisms/Media Type		
		TSOY (#/ml)	FERM (#/ml)	HACFU (#/ml)
22 top	-30	1.91E+04	3.70E+04	3.59E+05
22 mid		2.45E+04	1.56E+03	1.91E+04
22 bot	-11	2.45E+03	1.56E+03	1.56E+03
18 top	ND*	1.31E+05	1.59E+03	1.91E+05
18 bot	ND	2.45E+03	2.45E+02	1.91E+03
30 top	+28	1.26E+05	1.26E+04	1.26E+05
30 bot	+11	1.31E+02	1.56E+03	1.56E+03
56x top	-1	1.26E+05	1.26E+04	1.26E+05
56x bot	-34	1.31E+02	1.97E+04	1.97E+04
81x top	+35	1.56E+04	1.31E+03	1.60E+04
81x bot	-5	1.91E+03	1.26E+04	2.45E+03
92 top	-56	1.26E+04	1.56E+03	3.59E+04
92 bot	-40	2.75E+04	2.45E+03	1.97E+04

\* ND = not determined

<sup>1</sup> By A.T. Mikell, Jr., and J.C. Richardson, 1989, Kenneth E. Johnson Research Center, Consortium for the Space Life Sciences, University of Alabama in Huntsville, Huntsville, AL.

## October data

As in previous studies, certain wells were stratified with regards to their microbial content. Figure D5 represents the number of aerotolerant heterotrophic bacteria on a medium containing tryptic soy broth at a concentration approximately 10x that of HACFU medium. Wells 18, 30, and 50x reveal dramatic ( $>10x$ ) stratification. All wells using the low organic medium HACFU demonstrated higher numbers of bacteria at the top than the bottom (see Figure D6). The number of these oligotrophic bacteria in the middle depth were more similar to the bottom than the top.

Greater densities of aerotolerant bacteria normally coincide with higher ORP (Oxidation Reduction Potential) and dissolved oxygen values. These parameters are not always greater at the well surface (see previous reports and ACE data). This may be due to differences in horizontal flow within the well.

The ORP values for these wells ranged from -30 mV to +58 mV (Table D2). These ORP values would indicate that dissolved oxygen is limiting in these wells. The high number of those bacteria capable of fermentation of glucose (Figure D7) support this.

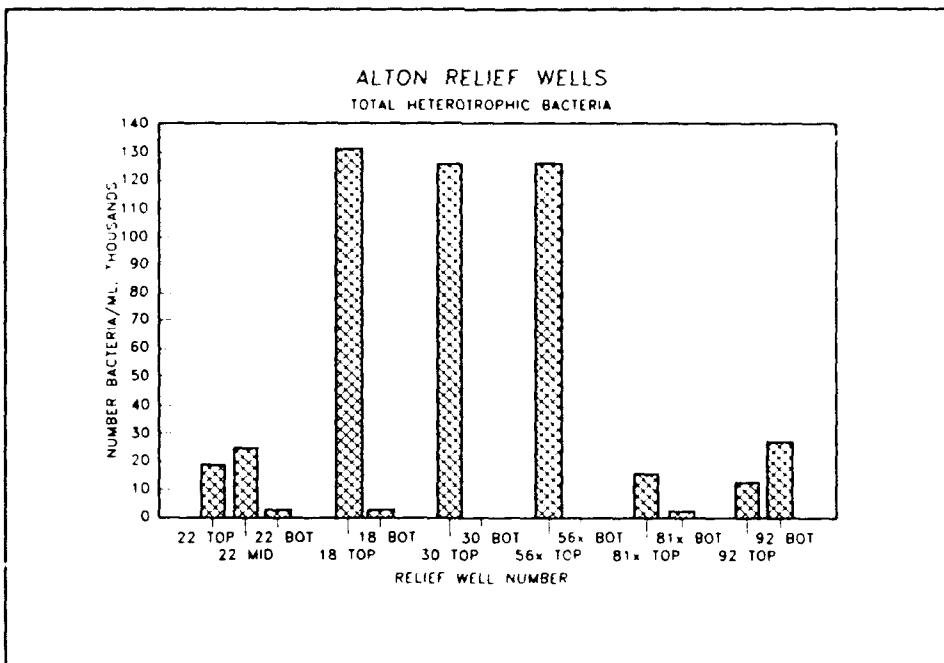


Figure D5. Total aerotolerant heterotrophic bacteria

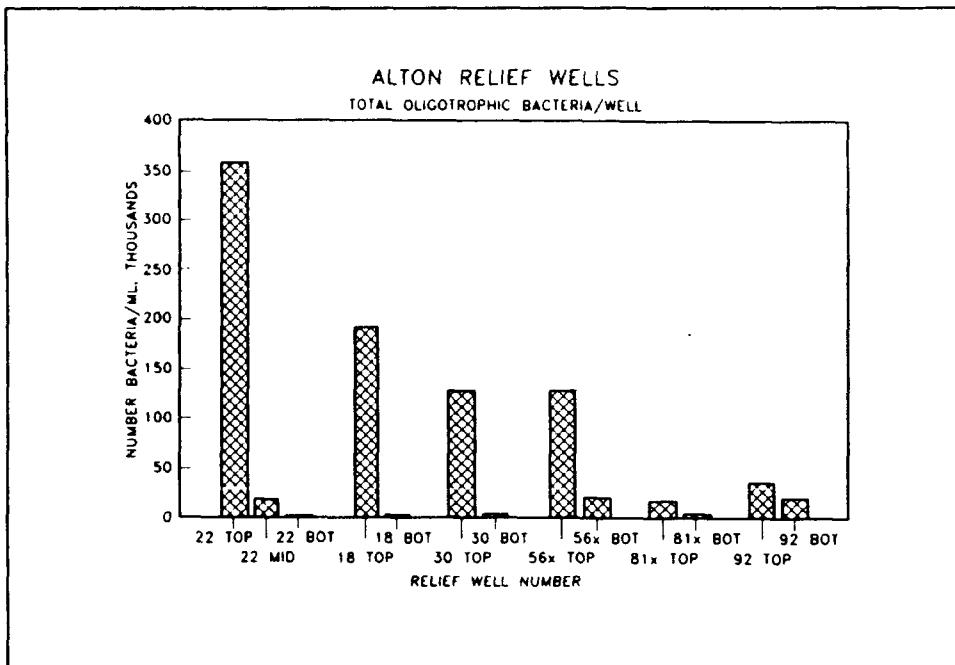


Figure D6. Total oligotrophic bacteria

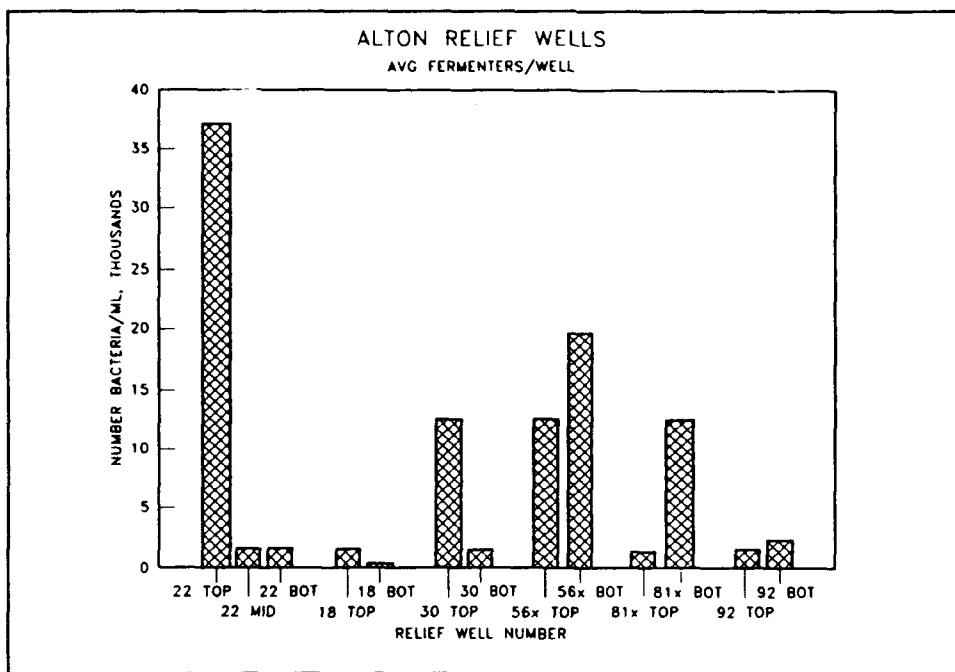


Figure D7. Total fermenter bacteria

### October/January comparative data

In comparing samples from January 1989 with October 1989, the data are limited. Only four wells were sampled on each period. In an effort to compare these periods, the aerotolerant heterotrophic bacterial counts were developed as ratios. A value of 1 would indicate no change. Two trends are apparent in Figure D8. Two of the wells sampled were actually lower in aerotolerant heterotrophic bacteria in October than in the January sampling (RW18 = 0.6, RW22 = 0.7). A significant increase in bacterial counts developed in the other two wells since the January sampling. RW92 increased in bacterial density approximately 100-fold, whereas RW30 increased nearly 400-fold.

The change in ORP (OCT/ORP - JAN/ORP) supports the bacterial data. Both RW30 and RW92 exhibited a significant negative shift in their ORP, -140 mV and -260 mV, respectively (Figure D9). This shift in ORP may indicate that the population of aerobic bacteria in these wells were metabolically active and reduced the oxygen content.

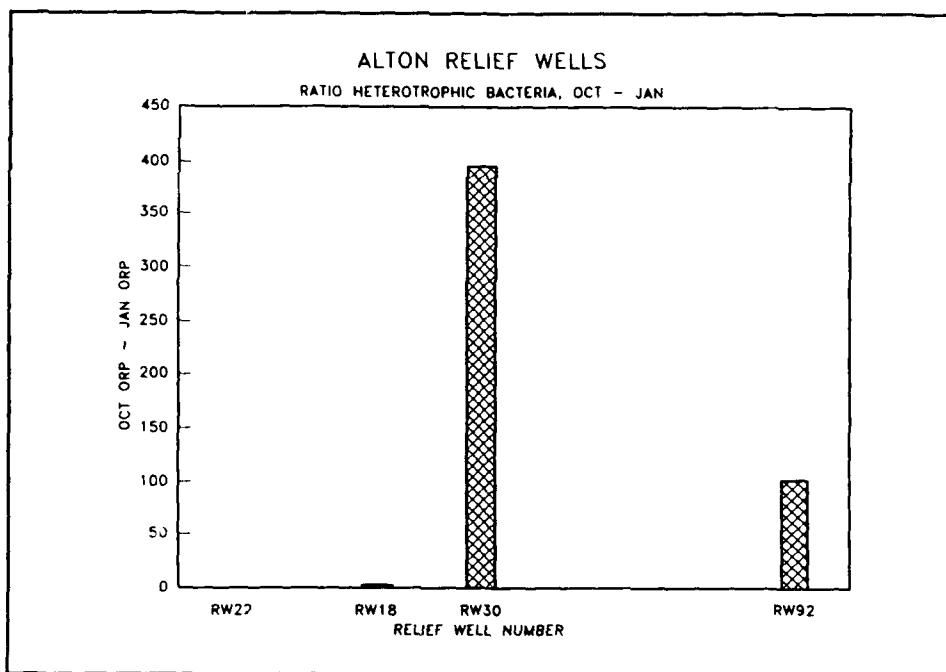


Figure D8. Ratio heterotrophic bacteria

As previously reported, differences between numbers of organisms grown on the tryptic soy medium and the oligotrophic medium HACFU in the past at Grenada, MS, and Denver, CO, wells have demonstrated some relationship to fouling (physical flow and/or pump tests and microscopic examination). A relationship appears to be a positive correlation between:

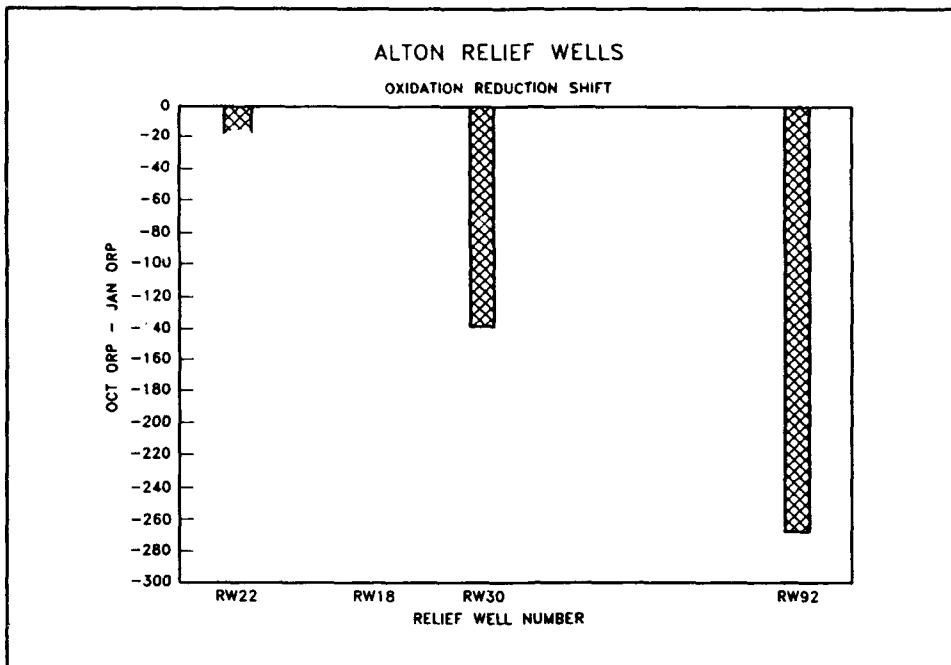


Figure D9. Shift in ORP

- Low total numbers ( $<10^4$ /ml) of viable bacteria (any medium).
- Increased ratios of aerotolerant bacteria grown on HACFU compared with tryptic soy.
- High ( $>+100$  mV ORP and an oligotrophic environment, with less nutrient loading and a reduced biomass (fouling).

Following these three criteria, all the wells sampled at Alton, IL, are prone to biofouling as all demonstrated an ORP of less than 100 mV. All the wells exceeded normal "clean" water levels of bacteria. When these wells begin to flow they may be expected to foul.

### Future work

In addition to the above parameters, sulfate-reducing bacteria, fluorescent direct microscopic counts, and membrane filtration/isolate identification need to be concurrently analyzed with each sample. Composite sampling may be used to reduce the overall sampling burden if preliminary water chemistry (dissolved oxygen, oxidation reduction potential) are performed first to select depths for the composite. More relief wells should be examined in an effort to statistically correlate both positive and negative factors associated with fouled wells.

# Appendix E

## Pump Test Results

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### General

There are any number of variables that can affect the calculations for specific capacity of a well including river stages and aquifer composition. River stages during the conduct of these tests are shown in Charts 1, 2, and 3. Aquifer variability is shown for the reach that includes Relief Wells 17 through 36 in Chart 4.

### Phase 1

Chart 5a presents the pump test results from Phase 1 before and after redevelopment efforts. The solid portions of the bars represent the results of the pretreatment pump tests, and the diagonally lined portions of the bars represent the change in performance resulting from redevelopment. Wells 21 and 43 were not treated because their specific capacities were initially found to be sufficient.

The highest specific capacity prior to redevelopment in Phase 1 was 148 gal/min/ft, for Well 18. The lowest value before treatment was 42 gal/min/ft for Well 29X. The mean for all wells was 148 gal/min/ft.

The test results following treatment ranged from a low of 62 gal/min/ft for Well 46 to a high of 173 gal/min/ft for Well 19. The mean of the posttreatment tests was 106 gal/min/ft.

Chart 5b illustrates the amount of improvement in gallons per minute per foot for each well, with the bar at the top showing the mean. Chart 5c illustrates the same improvement shown by Chart 5b as percentages of the Phase 1 initial specific capacity for each well. As before, the top bar represents the mean.

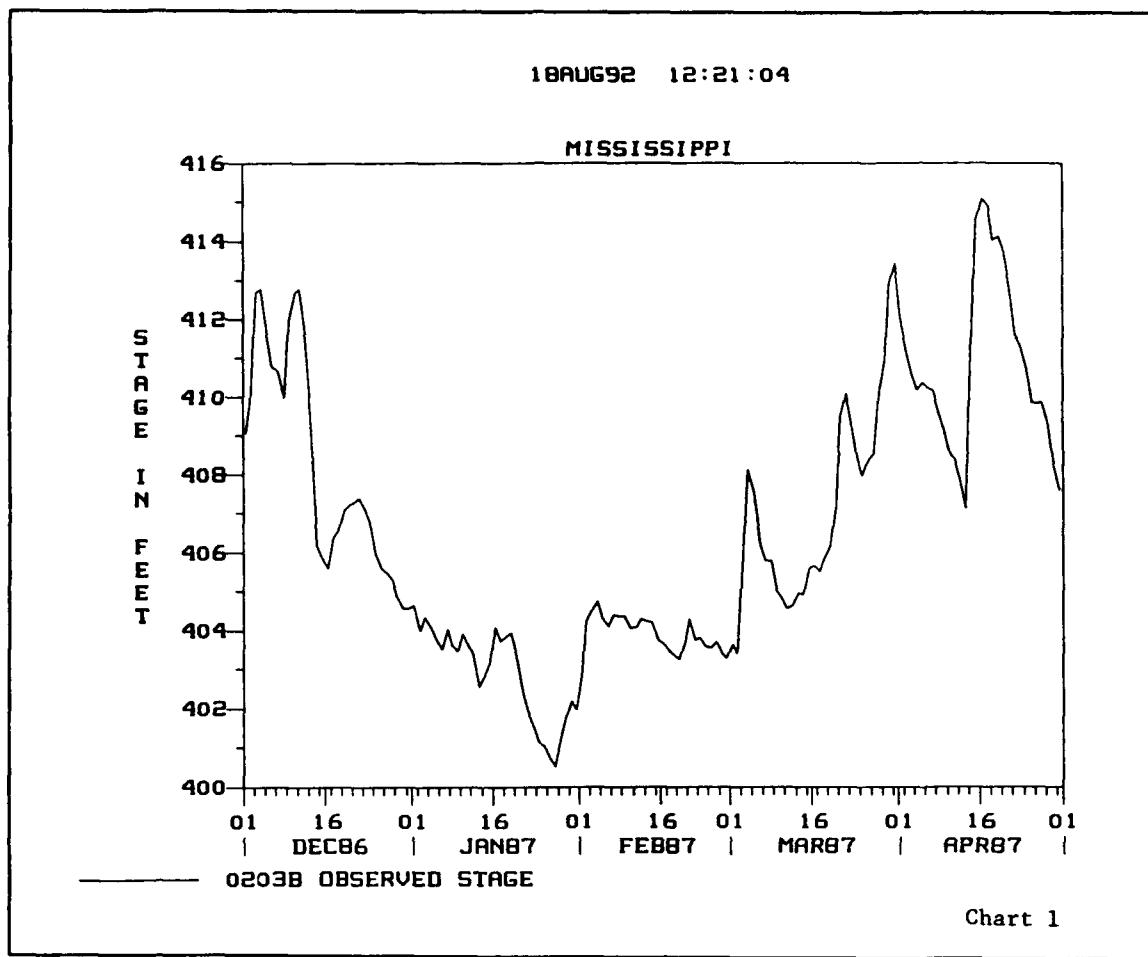
## Phase 2

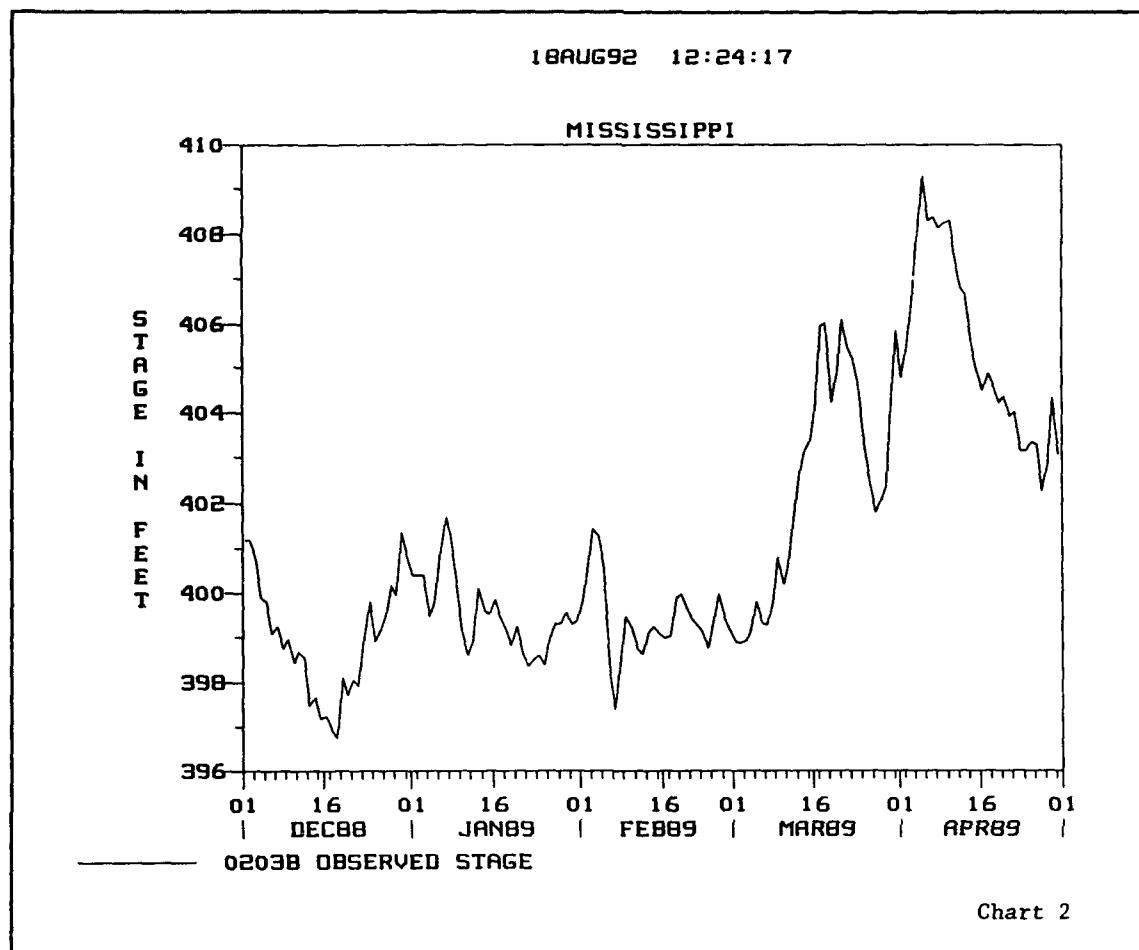
Chart 6a represents the specific capacities of the wells treated with the Blended Chemical Heat Treatment (BCHT) before and after treatment. The bars with the slanted line pattern on the left portion of the bar showed a minor amount of decline (less than 3 percent). The results before treatment ranged from 69 gal/min/ft (Well 44X) to a high of 234 (Well 17) with a mean of 133 gal/min/ft. Following treatment, the test results ranged from 80 gal/min/ft (Well 46) to 229 gal/min/ft (Well 20) with a mean of 147 gal/min/ft. Well 17 was not treated.

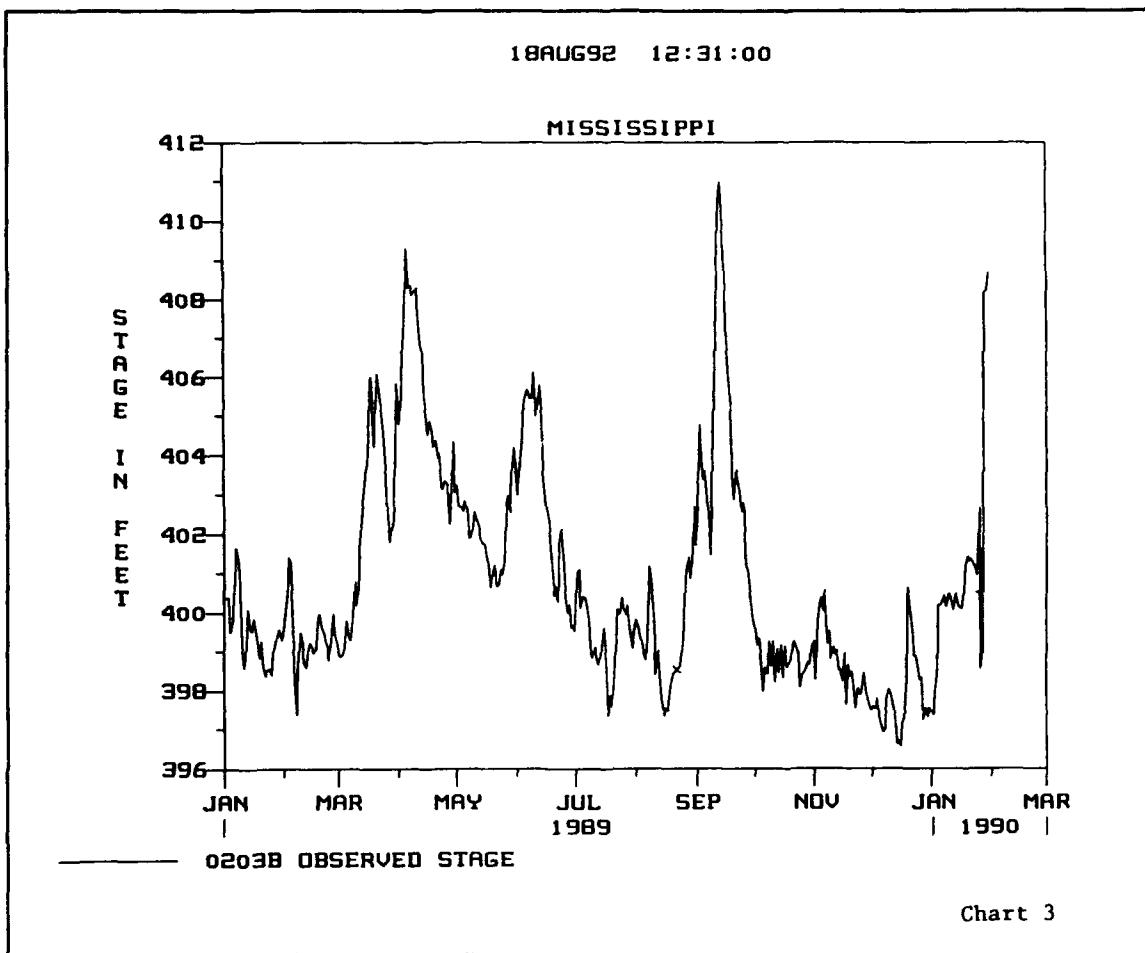
Charts 6b and 6c correspond to Charts 5b and 5c, illustrating the amount of Phase 2 redevelopment in the same fashion.

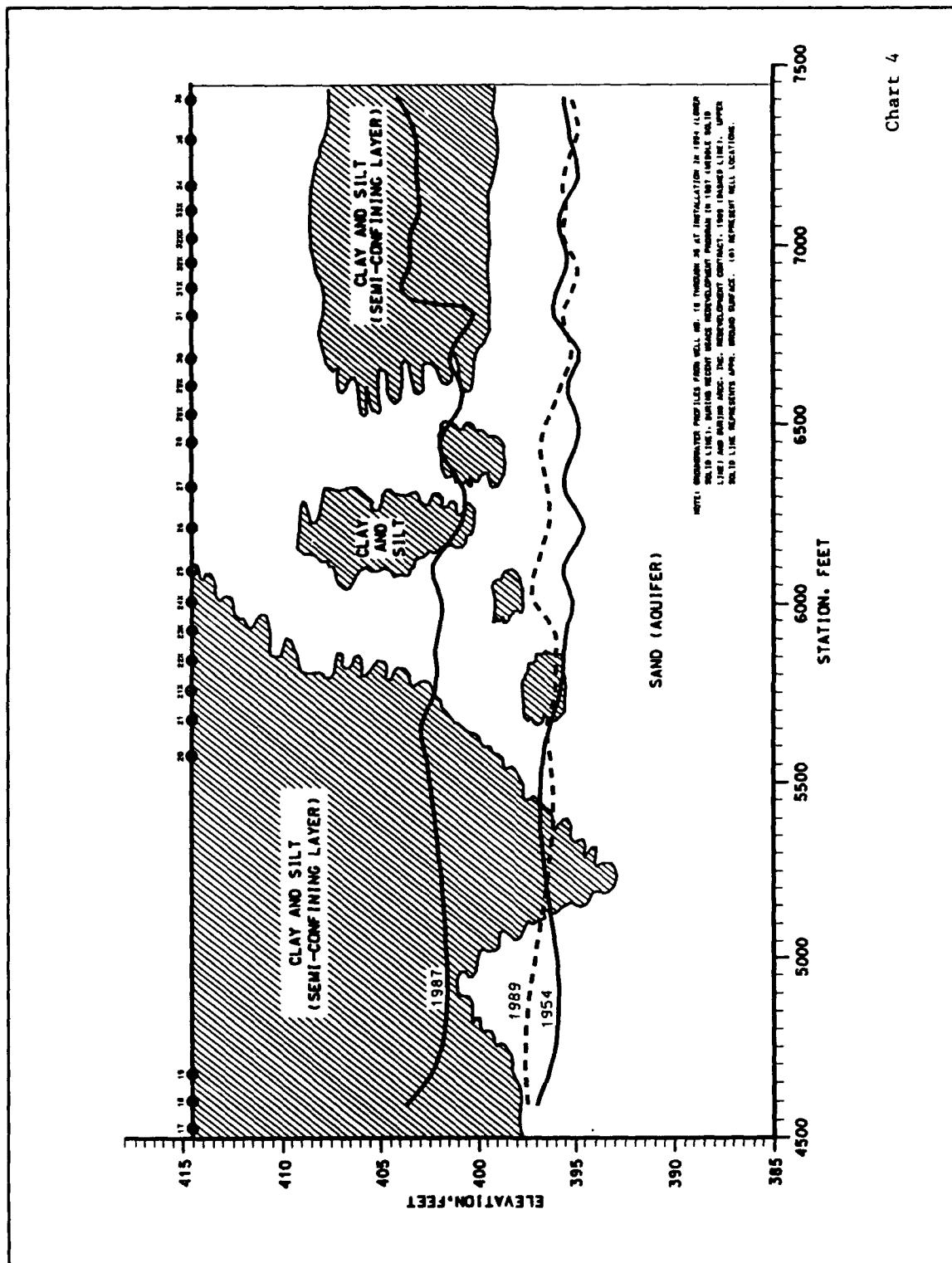
## Phase 3

Charts 7a, 7b, and 7c show the test data and change in specific capacity data for the wells treated in Phase 3. Those wells shown by Chart 3a with the slanted line pattern on the left side of the bars actually declined in performance in response to the redevelopment efforts. The changes in specific capacity are illustrated by Charts 7b and 7c. The groups of wells showing predominantly negative change in specific capacity were also subjected to the greatest ground-water depression during the dewatered stages of construction.

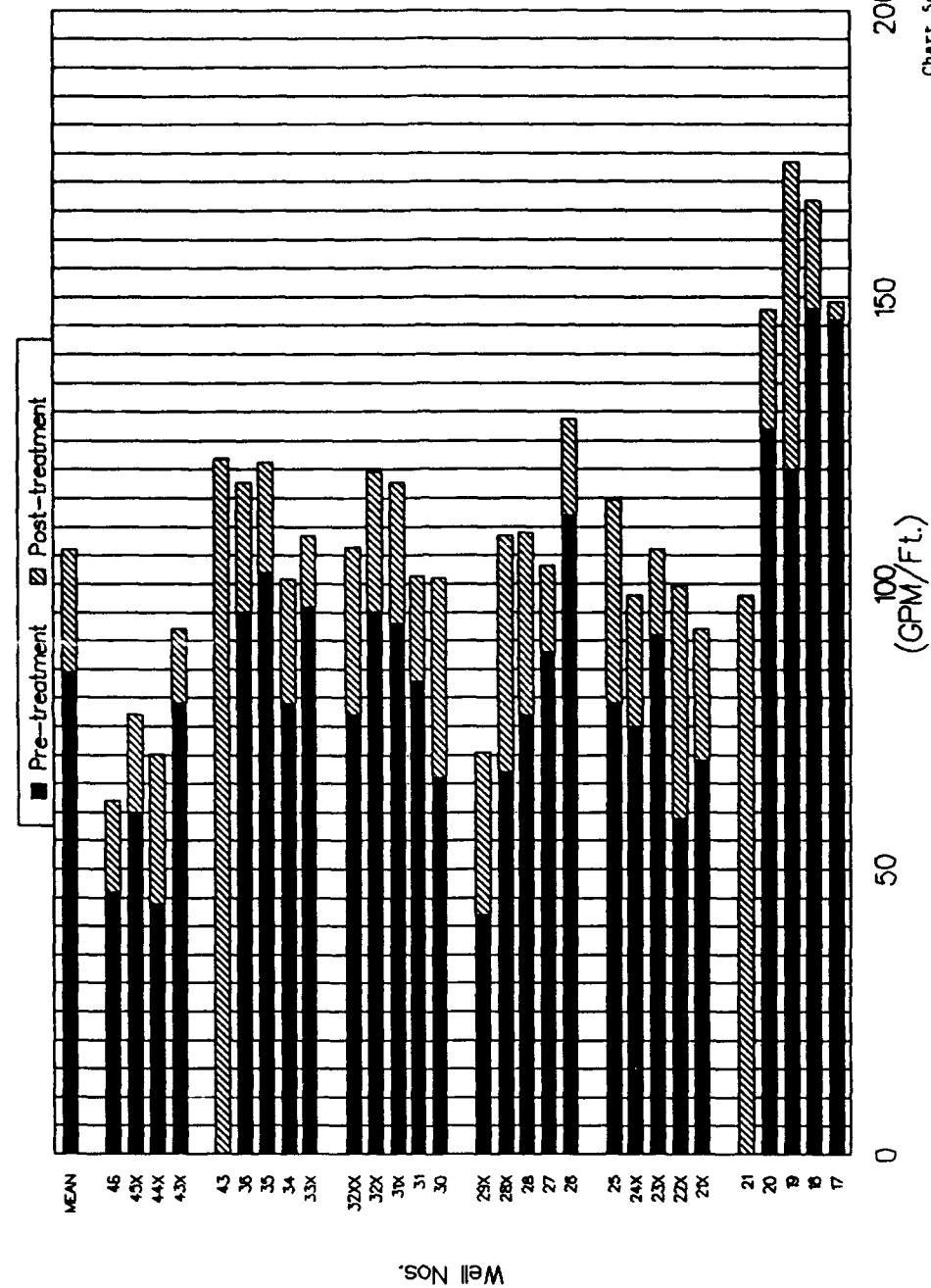








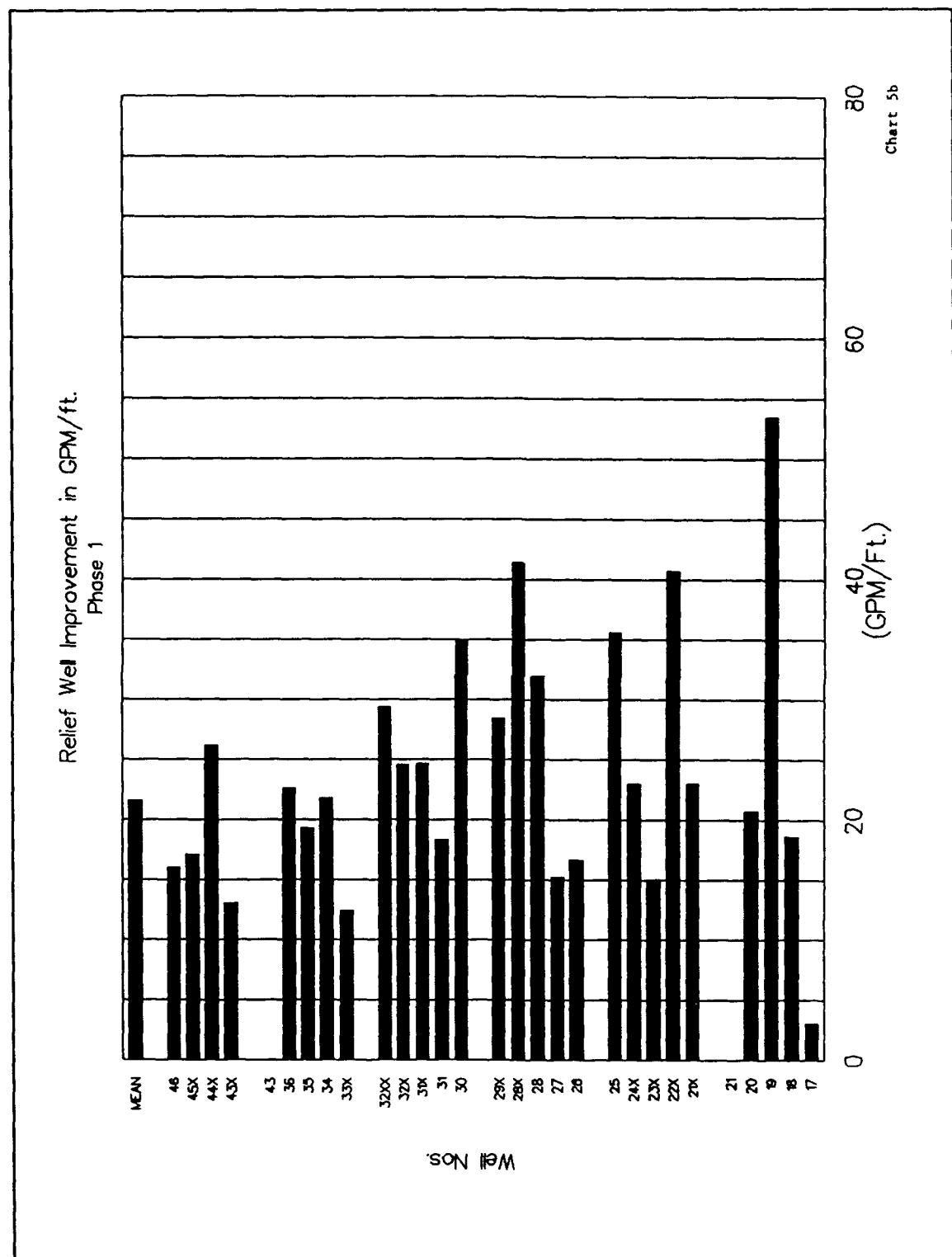
Relief Well Specific Capacity in GPM/ft.  
Phase 1

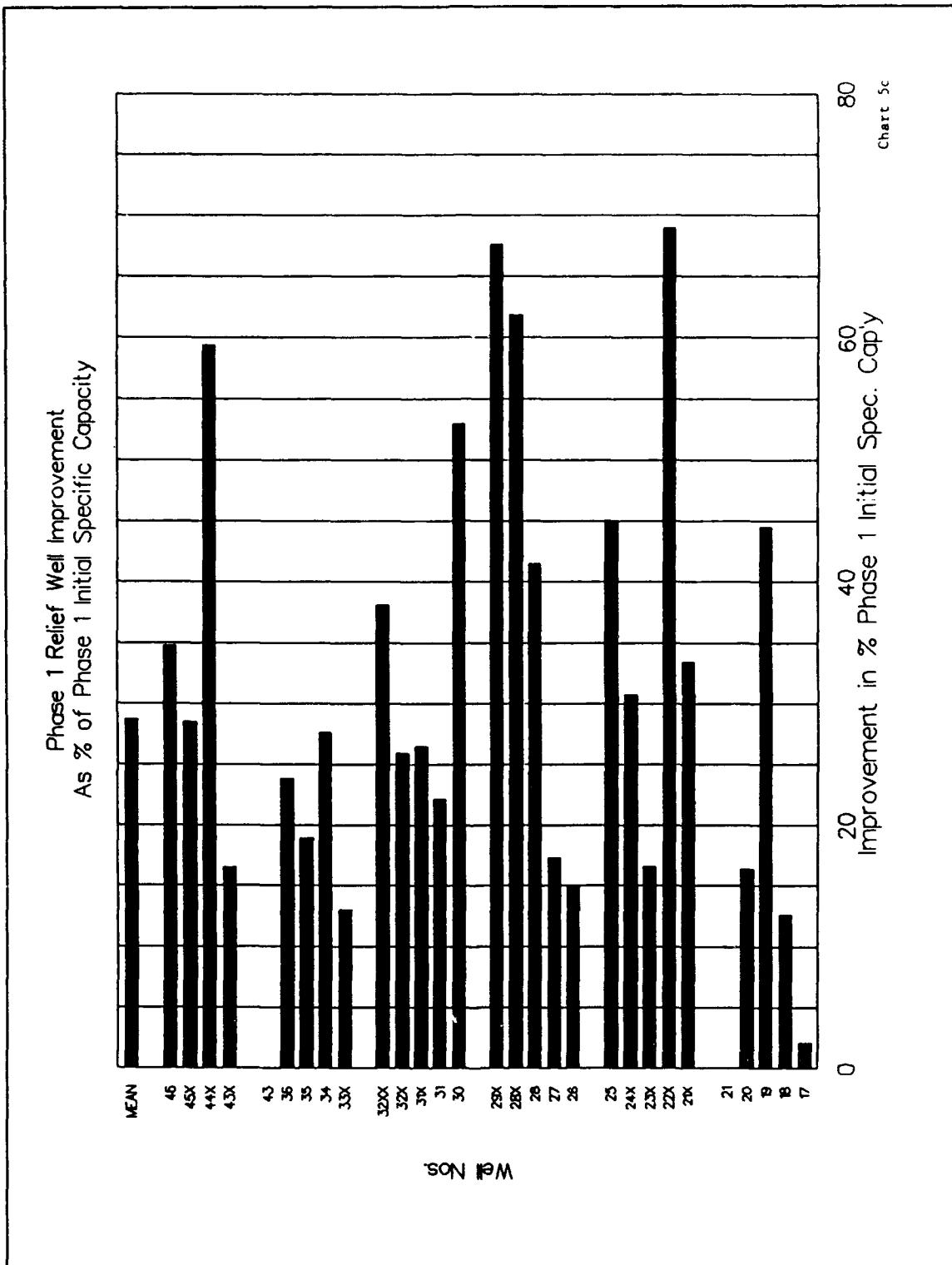


200

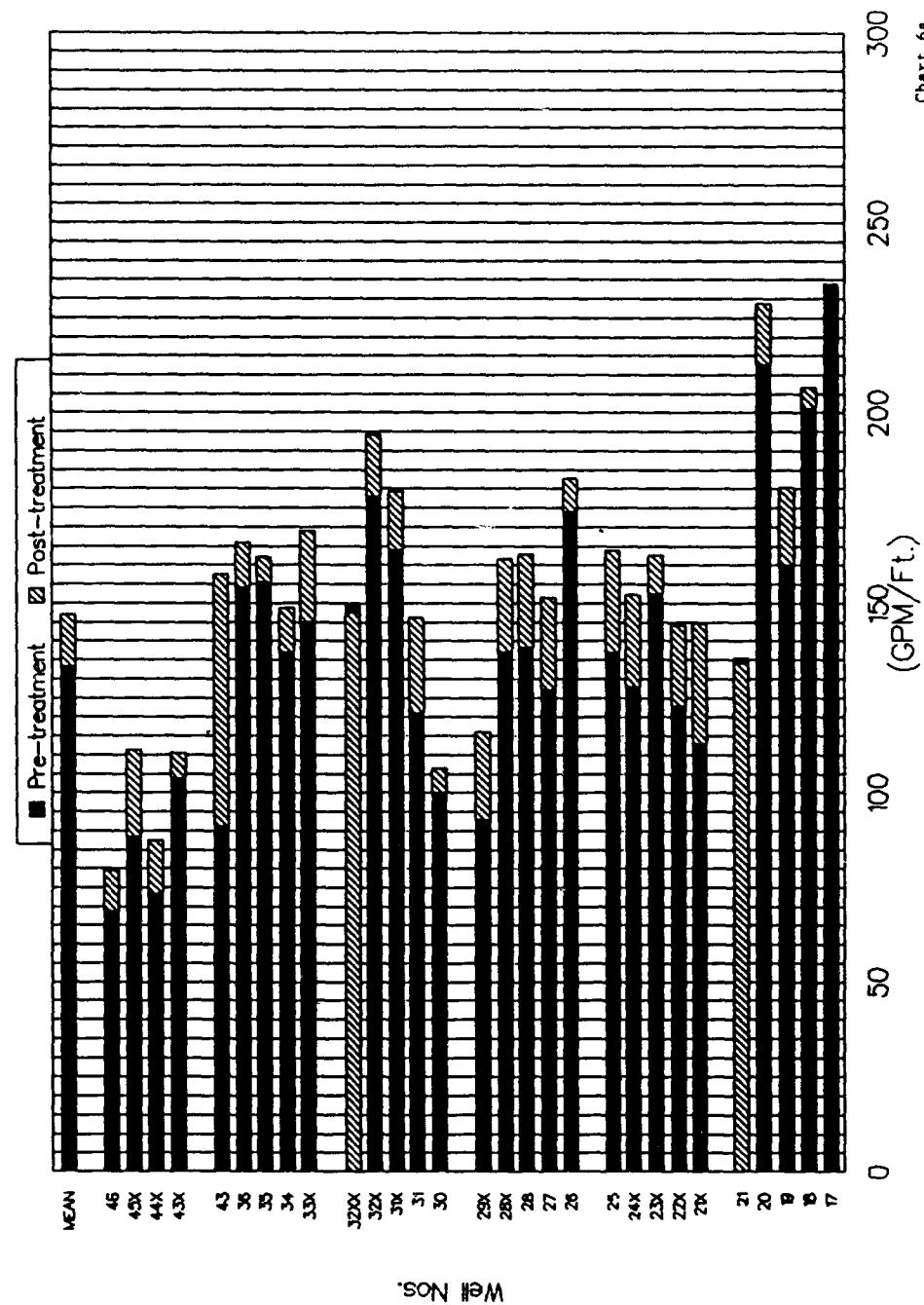
Chart 5a

150  
100  
(GPM/Ft.)

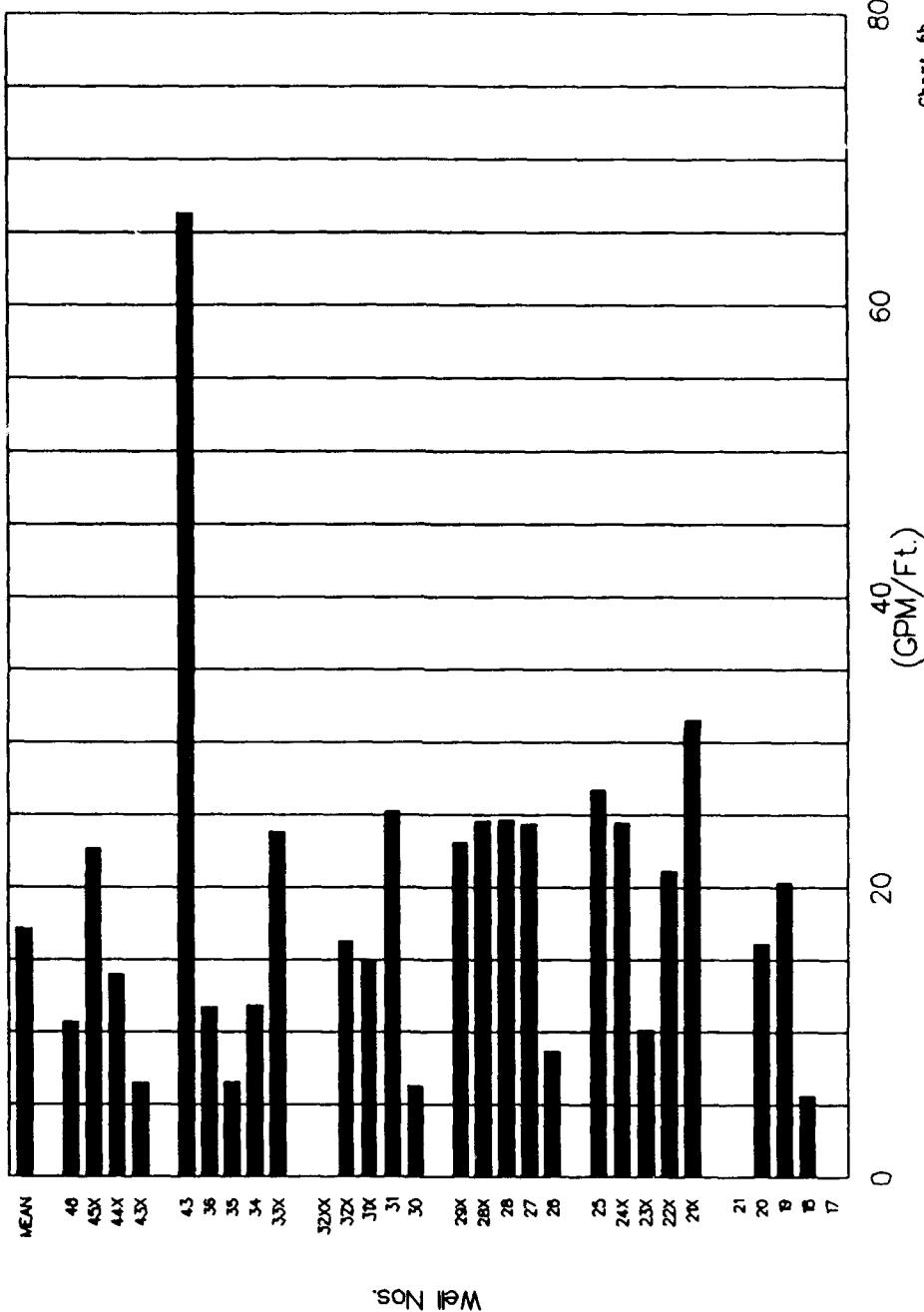




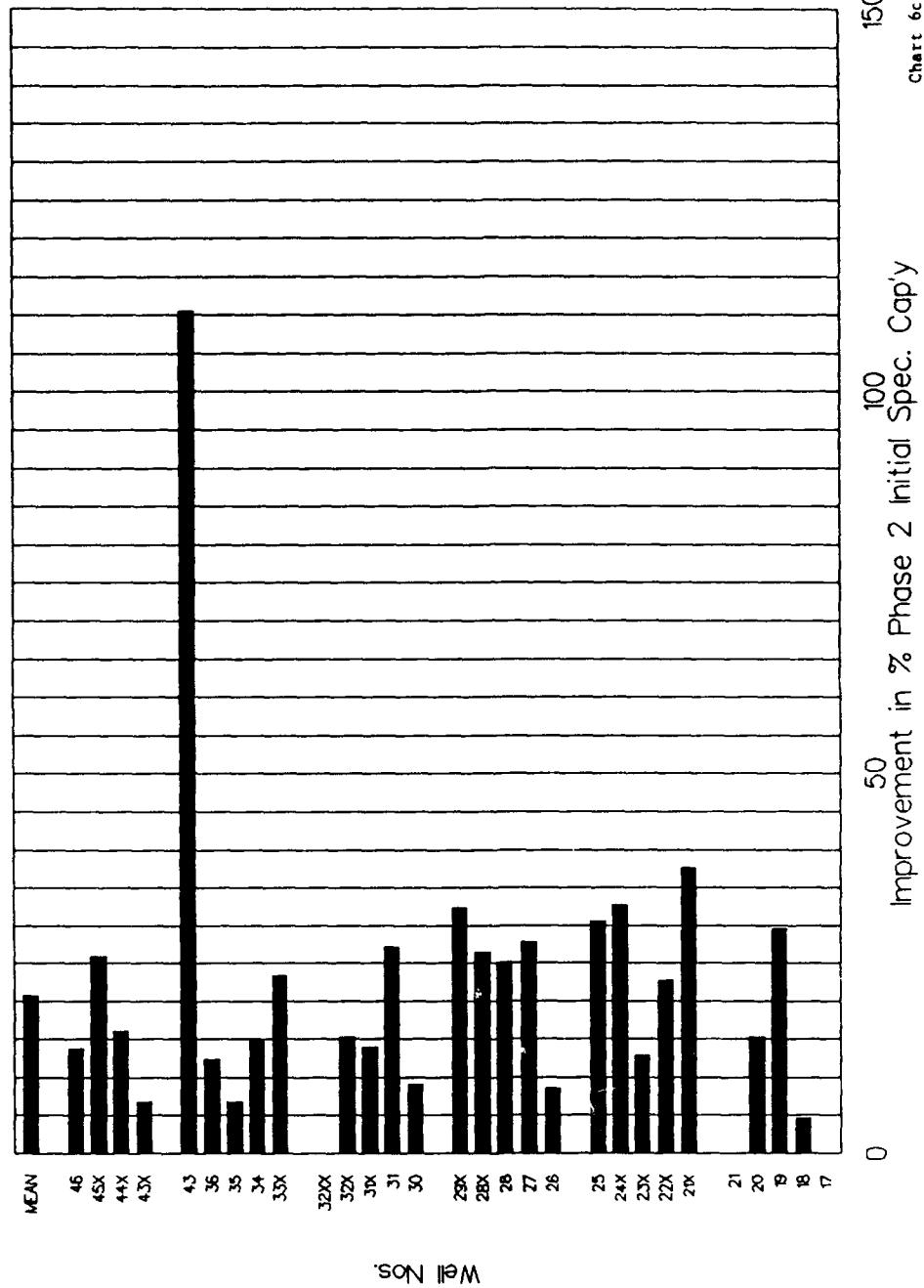
Relief Well Specific Capacity in GPM/ft.  
Phase 2



Relief Well Improvement in GPM/ft.  
Phase 2



Phase 2 Relief Well Improvement  
As % of Phase 2 Initial Specific Cap'y



150

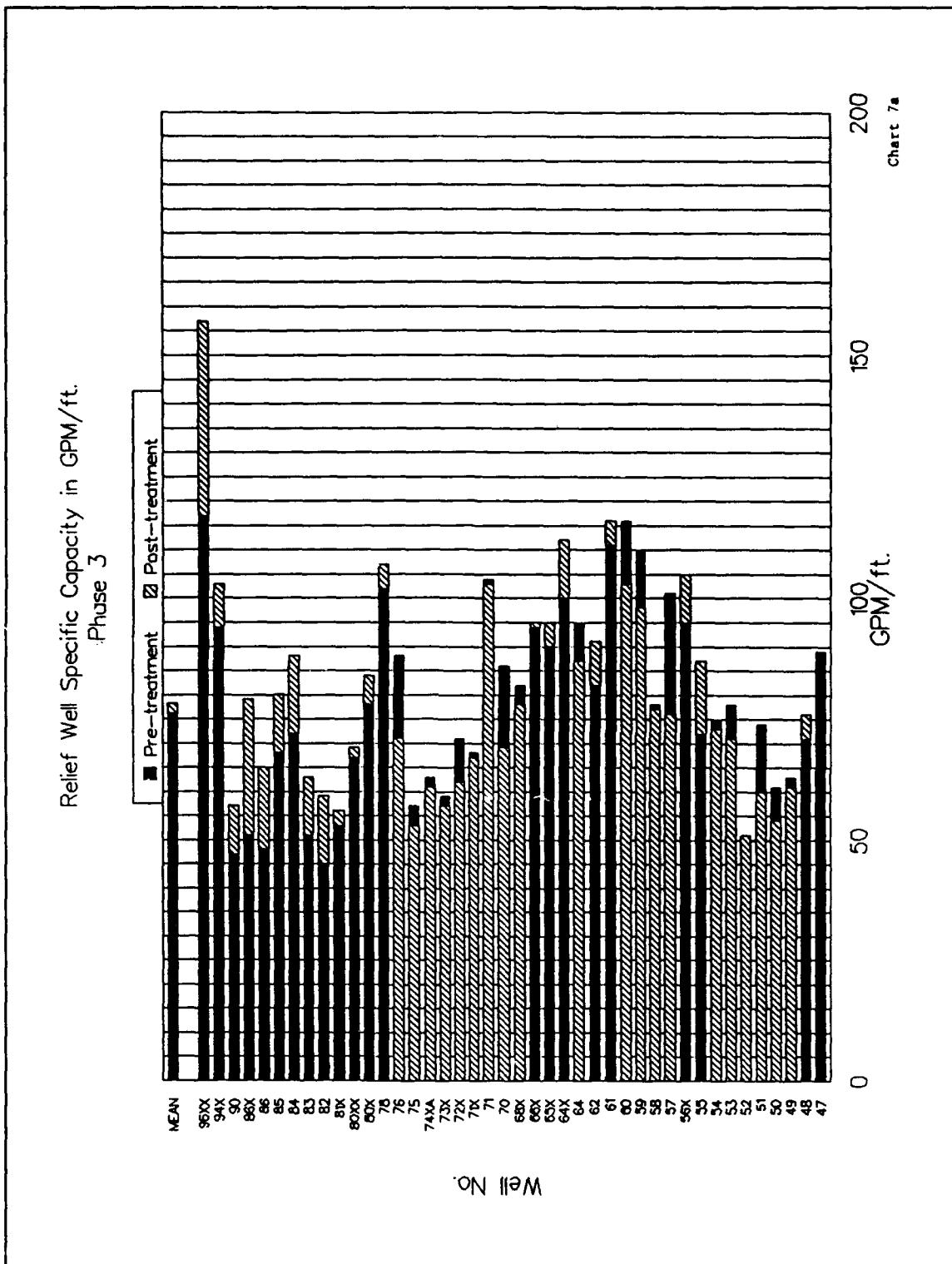
100

50

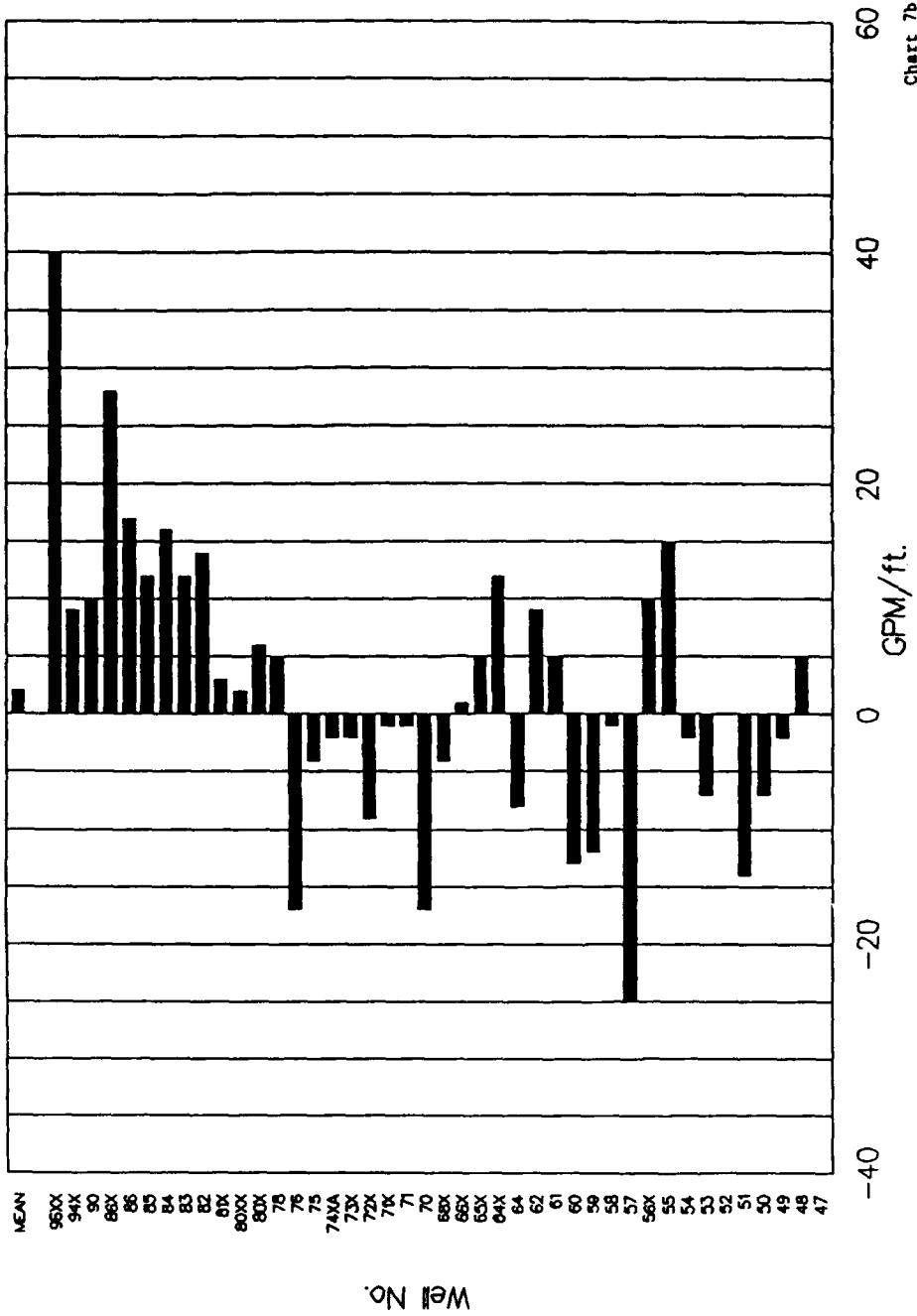
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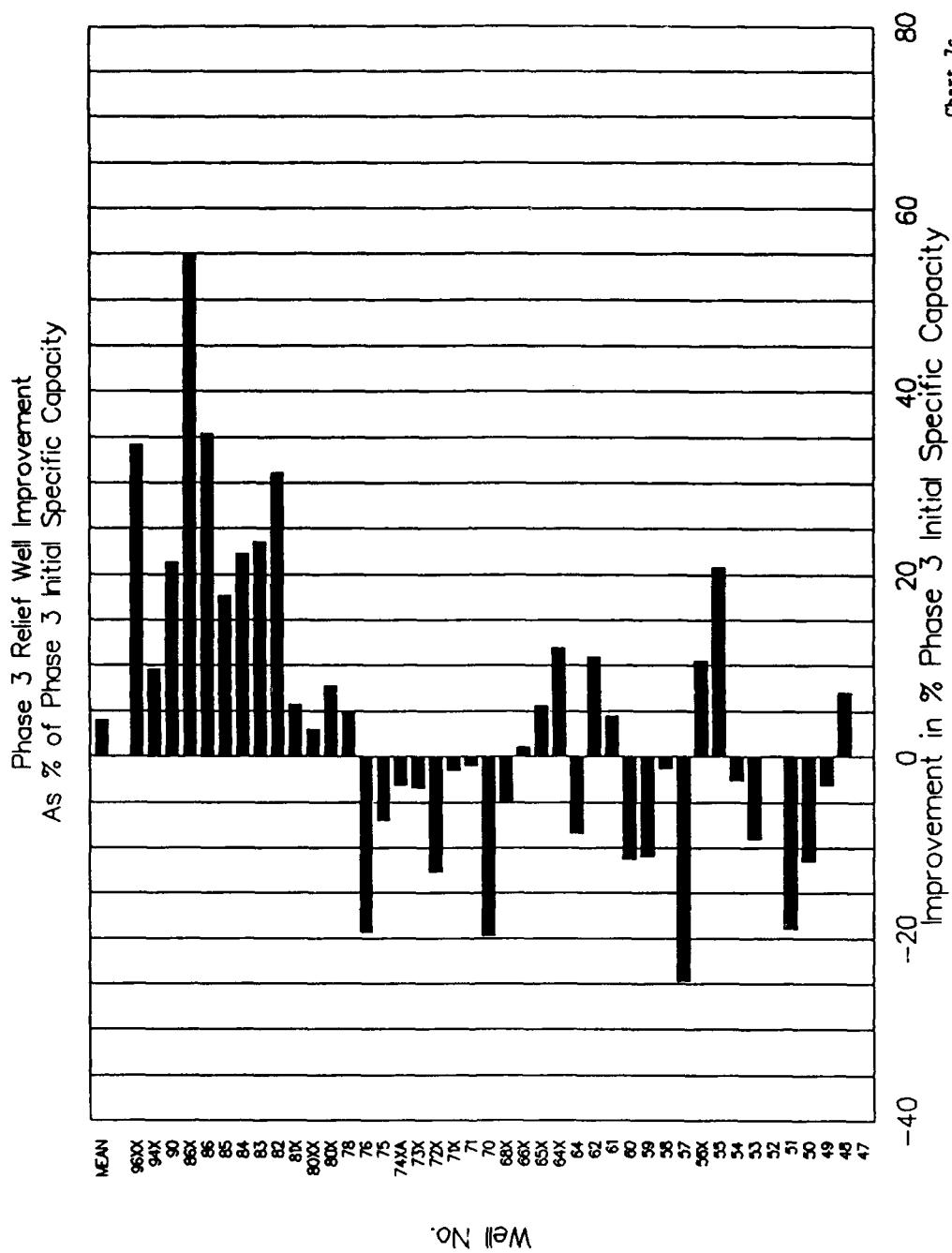
Improvement in % Phase 2 Initial Spec. Cap'y

Chart 6c



Relief Well Improvement in GPM/ft.  
Phase 3





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<p>Upgrading of the Upper Wood River levees resulted in their ability to hold back higher river stages, which in turn resulted in increased underseepage. A program of testing and redevelopment of the existing relief wells was undertaken to optimize the efficiency of existing measures, to assist in assessing the need for additional wells, and to assess current well cleaning procedures.</p> <p>The study resulted in a three-phase program consisting of (1) conventional cleaning procedures, (2) demonstration of a blended chemical high temperature (BCHT) procedure, and (3) a full-scale BCHT treatment on 28 wells. Conventional cleaning consisted of applying varying doses of trisodium phosphate and sodium hypochlorite to the well. The BCHT procedure introduces in several phases doses of chlorine and acid applied with steam injection.</p> <p>The results of the study showed that the BCHT procedure was more effective than conventional methods (even when heavy mechanical surging was used). On the demonstration wells, specific capacities were increased to design values with the BCHT procedure after strenuous (to the point of diminishing returns) conventional methods had been applied with limited success.</p>			
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